NAVAL POSTGRADUATE SCHOOL

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THESIS

INCREASED SURVIVABILITY OF THE
NATIONWIDE EMERGENCY TELECOMMUNICATIONS
SYSTEM (NETS) THROUGH REDUNDANT ROUTING

by

Carl Robert Pierson

March 1985

Thesis Advisor: J. W. LaPatra

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Increased Survivability of The Nationwide Emergency Telecommunications System (NETS) Through Redundant Routing

by

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I. INTRODUCTION

A. BACKGROUND

The Public Switched Network (PSN) is the major avenue of communication in the United States. The complexity of thousands of hierarchical telephone offices, millions of miles of cable and other media trunks is the vital circulatory system of all communications, digital and voice.

The network is exposed to the hazards of catastrophies, either localized or nationwide. These catastrophies include natural disasters, such as earthquakes, disasters of technology, for example, dam failures, and man-made disasters, i.e., war.

The network needs to stay alive and manage the burden of vital communications, information transfers which are required for National Security and the general public well-being. When arteries of the network are severed, the flow of this crucial information must be rerouted around the damaged or destroyed centers. The switched network must be able to provide two-way communication between any two users, at any two points in the United States.

The importance of routing redundancy, multiple communication paths between any two points can not be overemphasized. The surviving links and nodes must assure this capability to preclude a total communication blackout in the event of subsequent disasters.

The Nationwide Emergency Telecommunications System (NETS) Class 4 and 5 Switch Study is a comprehensive study initiated to determine the impact on telecommunications of various types of calamities. The public telephone network's survivability in emergency situations is one of the focal points of the NETS study.

B. FORMAT OF THE THESIS

This thesis uses an analytical approach to determine the importance of redundant routing through both multiple geographic and multiple media routing. It includes an overview of the telephone network elements, the switching offices, trunks, and routing schemes.

The study evolves from an examination of general network path characteristics, to a discussion of sensitivity analysis of the telephone network, and finally creates a method of measuring the network's survivability in the event of a national emergency.

Some of the major issues discussed in this study are:

1. Why is redundant routing essential ?
2. What are the existing architectural designs which facilitate redundancy ?
3. What measure of survivability can be assigned to a network design ?
4. How can redundancy in the network be improved ?

This thesis is not an economic evaluation of the telephone network. It addresses the effectiveness of existing network designs, makes recommendations for design enhancements for survivability, and proposes solutions for the guaranteed communications path between two points.

II. NETS AND PSN--AN OVERVIEW

The study of the redundancy of routing in the PSN and its affect on the NETS research begins with a presentation of both the NETS model and the PSN. This chapter will present a brief overview of each of the systems to acquaint the reader with the elementary concepts of both models. Later chapters will evolve from this basic discussion to more detailed examination of the systems.

A. NETS

Research on NETS is sponsored by the National Communication System (NCS). The NETS study examines the PSN (plus other dedicated and common carriers) under conditions of emergency. The NETS model is dynamic because it may take on any form depending upon the nature of the emergency and its affects on telecommunication.

The types of emergencies which would cause NETS to be invoked include but are not limited to the following (Figure 2.1):

Natural Disasters	Technological Disasters	Man-made Disasters
Earthquake	Explosion	Terrorism
Hurricane	Dam Failure	War--Nuclear
Tornado	Oil Cutoff	War--Conventional
Flood		

Figure 2.1 NETS Emergencies

The NETS project includes studies of:

(1) Emergency scenarios

(2) Effects of emergencies on the PSN

(3) Demand of telecommunication during emergencies

(4) Precedence on NETS

(5) Blocking on NETS

(6) Data communication

B. PUBLIC SWITCHED NETWORK

The Public Switched Network is operated by the Bell System and Bell-affiliated post-divestiture companies. It is comprised of various switching equipment and centers, telecommunications media, telecommunications equipment, and users.

The network provides for communication between users of more than 150 million telephones and computers which support both business and residential (private) communications. It enables both analog (voice) and digital (data) interchange.

C. AREA SYSTEM CONCEPTS

The network is composed of two area systems concepts, the local exchange area system and the long haul system. The local exchange area system serves end users within a few miles of each other. Voice frequency transmissions are handled on multipair wire cables as are digital communications. Areas of higher density use coaxial cables and radio transmission to accommodate the increased demands.

The long haul system extends from a few miles to several thousand miles. It serves users nationwide via various telecommunications media including coaxial cable, microwave radio and satellite relays, submarine cable, and wave guide. [Ref. 1]

D. SWITCH FACILITIES

To connect the different systems the network employs two basic switch facilities. The local switch connects loops

(local exchanges) to loops and loops to trunks (long haul). The toll switches connect trunks (long haul) to trunks. In large metropolitan areas the PSN uses tandem switches to connect trunks to trunks.

The switching systems (local and toll) evolved to reduce the number of lines necessary to connect all users to each other. Consider six users, without a switch, who require communication between themselves. The number of interconnecting lines for all users to access all other users is 15. See Figure 2.2. As the number of users increases to seven, the number of required lines expands to 21. The number of links required to interconnect all users can be found using the formula C = [n(n-1)]/2, where C is the number of links and n is the number of users. [Ref. 2]

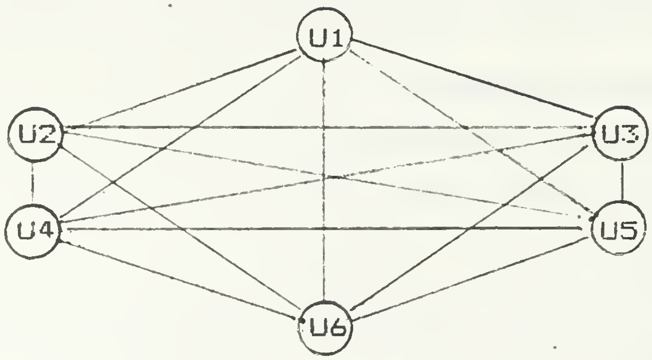


Figure 2.2 End Users/Required Links Without Switching

The central switch concept reduces the number of links to C=n, again where n is the number of users. See Figure 2.3.

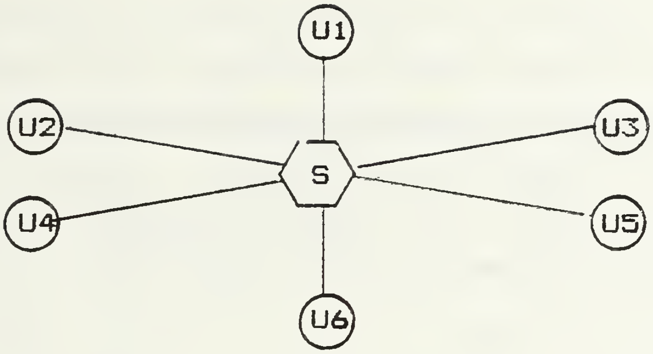
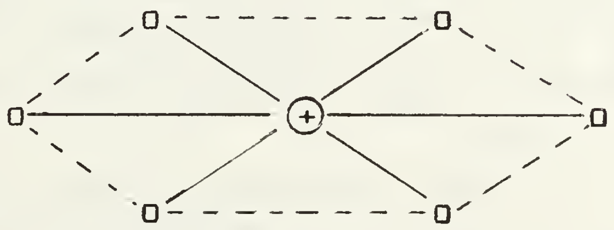


Figure 2.3 End Users/Required Links With a Switch (S)

E. TANDEM SWITCHES

The tandem switch was developed to accommodate heavy traffic between three (3) or more central offices. Many small sources of telephone traffic can be pooled into one large tandem trunk connecting any given central office to a tandem office. Consider the case of six (6) central offices with required communication between all offices. Adjacent offices are connected by direct trunks. Non-adjacent offices are connected via the tandem office. The tandem office serves two functions in this case. This office provides for non-adjacent central office interconnection and it enables adjacent office communication to continue when the direct trunk between the central offices is saturated. See Figure 2.4.



- - - Direct Trunks

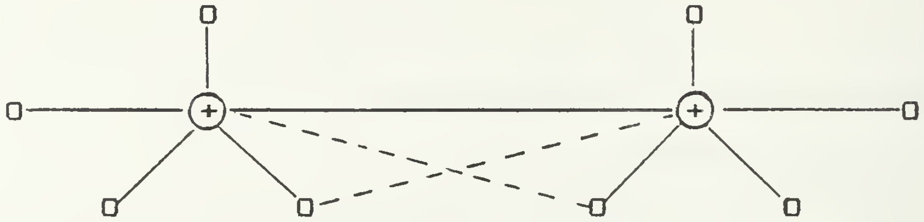
O - Central Office serving local loops

—— Tandem Trunks

+ - Tandem Office

Figure 2.4 Tandem Office/Central Office Interconnection

As the number of central offices increases, it is advantageous to group central offices into sectors, with each sector served by a different tandem office, located near the geographical center of the sector. Figure 2.5 illustrates the sector tandem local network concept with direct trunks connecting high communication rate central offices. [Ref. 3]



- - - Direct Trunks　　O - Central Office
——— Tandem Trunks　　+ - Tandem Office

Figure 2.5 A Tandem Local Network

F. SUMMARY

A study of routing redundancy in NETS must be based upon a thorough understanding of the PSN. The switched network, with its multitude of trunks and offices sets the scene for further examination of the network. It has been shown that the PSN is comprised of a series of links (trunks) and nodes (switching offices) which enable various routing of telecommunication signals over more than one path. The local switch concept reduces the number of links necessary to connect end users. The tandem switch alleviates heavy traffic between offices and provides redundant routing between PSN offices.

Chapter III will unite the local and area system concepts of the PSN in a discussion of the class office hierarchy and switching principles.

III. PSN HIERARCHICAL CLASS OFFICES AND SWITCHING

Chapter II introduced the basic concepts of Switching, Central Offices, and Tandem Offices. This chapter will further develop the switching and office concepts by presenting the hierarchical class office structure and some more switching concepts. The class office architecture of loops, trunks, and offices form the physical portion of the switched network links and nodes. The routing of telecommunication signals through the network over loops and trunks, through numerous classes of offices and over various routes adds to the redundancy of the PSN and increases the survivability of the NETS model.

A. BASIC STRUCTURES

To review, a trunk is a communications path between two switching systems. A loop is a circuit which connects an end user's telephone to a switch (or central office). The loop is usually a pair of wires which extends from the user to the central office from zero to several miles in length. 90 percent of all loops are less than 20,000 feet long. Figure 3.1 presents a basic 2-Level hierarchy with users, central offices, loops, and an intermediate office. The central office is normally designated as a Class 5 hierarchical component. The intermediate office is in this case is a Class 4 or Toll office component. [Ref. 4]

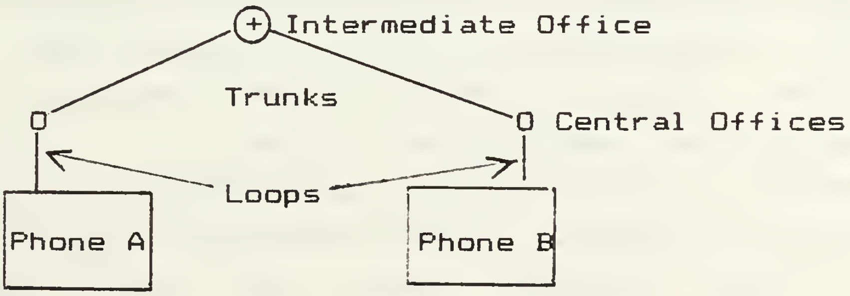


Figure 3.1 A 2-Level Hierarchy

A 3-Level hierarchy incorporates the 2-Level components, the Central and Toll offices plus a superior component, the Primary Office or Primary Center. Figure 3.2 illustrates the 3-Level hierarchy architecture.

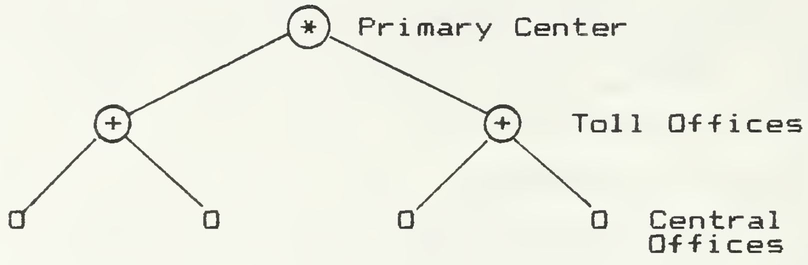


Figure 3.2 A 3-Level Hierarchy

The 4-Level hierarchy combines the 3-Level components plus a superior component-the Sectional Center (Class 2 Office) which serves as the master switch to the Primary Centers (Class 3) and their subordinates components (Class 4 and 5). Figure 3.3 summarizes. [Ref. 5]

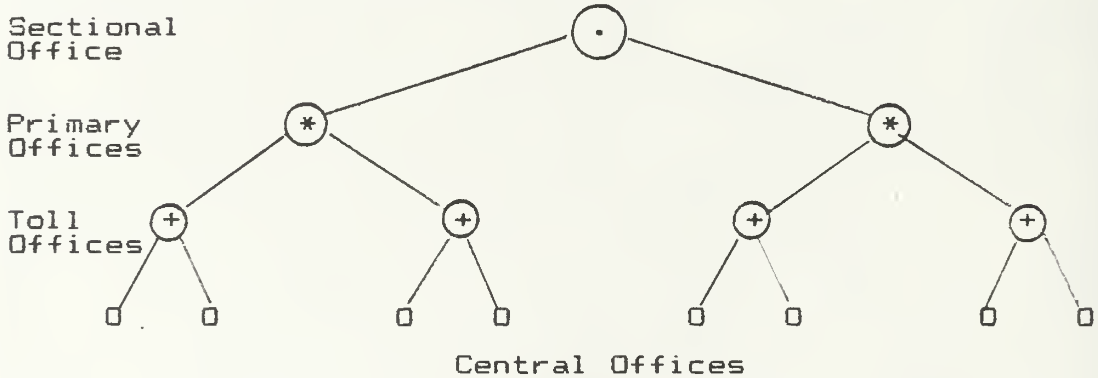


Figure 3.3 A 4-Level Hierarchy

The final hierarchy, level 5, represents all of the switching components of the PSN. The top level component-the Class 1 Office or Regional Center serves the Class 2 offices and their subordinate offices.

The PSN for Canada and the United States is divided into twelve (12) regions. Each region has one (1) regional center. These regional centers are joined together by trunks. This final architecture enables end-to-end

telephone communications between any two users of the PSN. Figure 3.4 presents the final architecture. [Ref. 6]

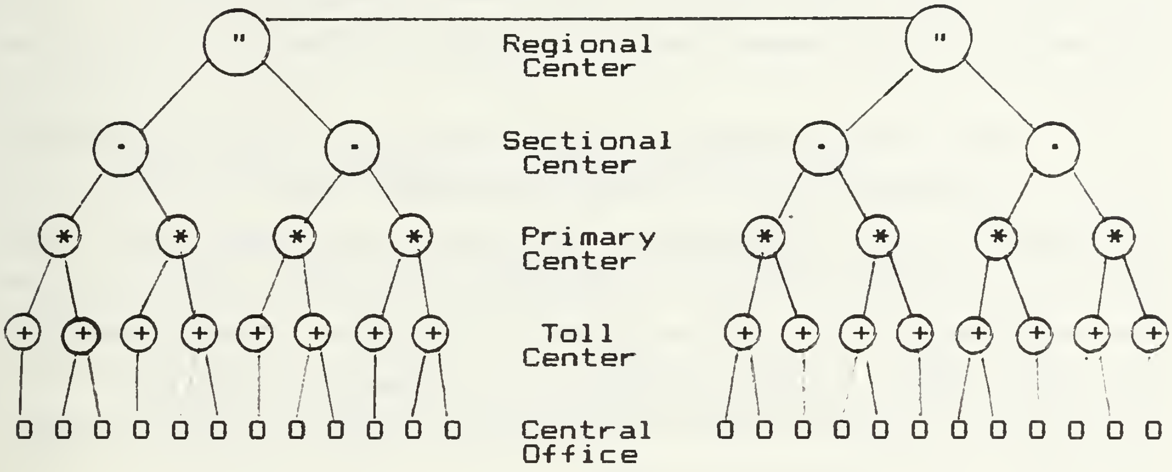


Figure 3.4 A 5-Level Hierarchy

As of 1984 the 5-level hierarchy of the PSN throughout the U.S. was composed of the following offices and numbers:

19000 Class 5 (Central/End) Offices
1300 Class 4 (Toll) Centers
230 Class 3 (Primary) Centers
67 Class 2 (Sectional) Centers
10 Class 1 (Regional) Centers. [Ref. 7]

B. TYPICAL SWITCHING THROUGHOUT THE 5-LEVEL HIERARCHY

For any toll call to a particular destination to be accomplished, the PSN offices have a prescribed set of high-usage groups of lines that it tries in a specified order. As a last resort, the network typically attempts to complete the call on the final group. Figure 3.5 shows a nominal toll network pattern for the level 5 architecture. As shown in the figure, the Class 5 (Central/End) office is not always subordinate to a Class 4 (Toll) office; it may be connected directly to any superior level component. [Ref. 8]

1. Switching Rules

The basic rule for routing a toll call is to complete the connection at the lowest possible level of the hierarchy. This provides for using the fewest trunks in tandem.

The call, originating through Point A (Central Office) will first go to the Toll Center-Point B, then to the Primary Center-Point C. To reduce the number of trunks spanned, the network will attempt to route the call through the destination Toll Center-Point D and then to the destination at Point Z (End Office). To provide an algorithmic approach to the routing scenario the network will attempt routing in the following order:

Path 1 A-B-C-D-Z

Path 2 A-B-C-E-D-Z

Path 3 A-B-C-G-E-D-Z

Path 4 A-B-C-G-H-J-F-E-D-Z (The final group)

Figure 3.5 presents a typical switch pattern. [Ref. 9]

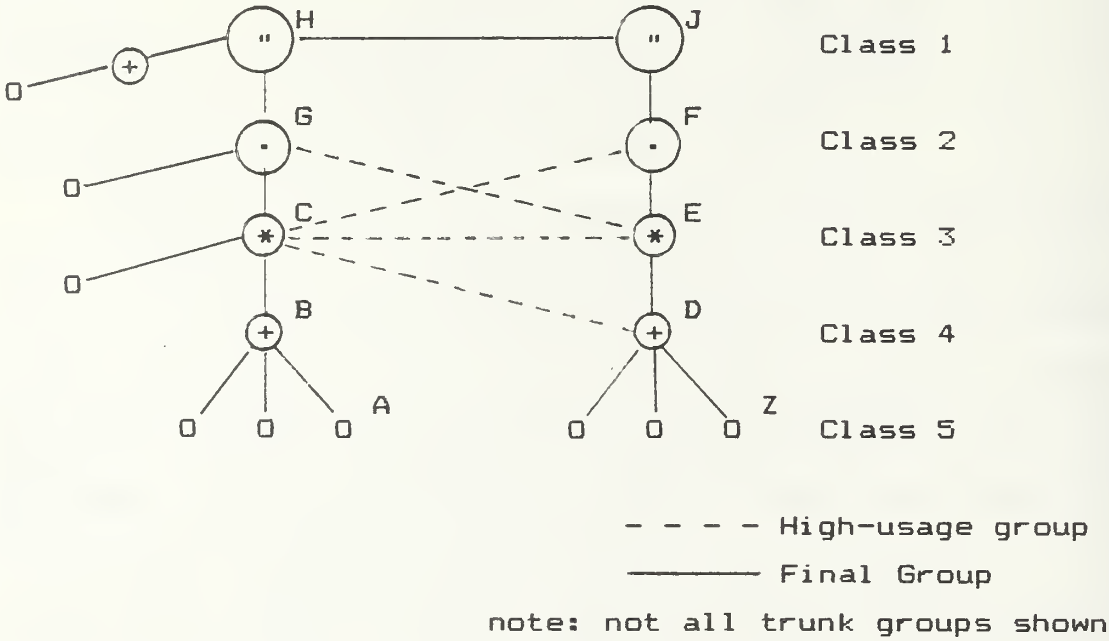


Figure 3.5 Nominal Toll Network Switch Pattern

C. LOCAL NETWORK AND TOLL NETWORK INTEGRATION

The local (tandem local) network discussed in Chapter One is integrated with the toll network (described in this chapter) in various fashions. Three common examples of the integration are:

(1) A single office may perform a dual function:
(a) as a tandem for local traffic and,
(b) as a Class 4 Toll center for toll traffic.

(2) Each Central Office may segregate traffic, by sending local traffic to a dedicated tandem office and toll traffic to a dedicated toll center.

(3) Typical network integration uses a combination of examples (1) and (2). Outgoing traffic is routed via a Toll Center (for customer billing), but incoming traffic is routed directly via a Primary Center to a local tandem office for distribution to Central Offices. [Ref. 10]

D. SUMMARY

The PSN class office hierarchy comprises the architecture necessary to complete a telephone call between any two users of the network. The 5-Level hierarchy of offices from the local switch--the Central office to the long-haul switch--the Regional office defines the nodes of the PSN model. The switching scheme for the routing of a toll call through the network hierarchy illustrates a built-in redundancy of signal paths necessary for NETS survivability.

Chapter IV will introduce another method of redundancy in the PSN, the redundancy through various types of telecommunication media.

IV. PSN SIGNALS, CHANNELS, AND MEDIA

The last two chapters of this study discussed switching, PSN office hierarchy, and routing of calls through various trunks. This chapter will take a more detailed look at the media of trunk components of the PSN.

Between any two users of the network there is a complexity of offices and switching systems that connect them. The links which connect the users to the various nodes and the nodes to each other may be comprised of many types of media. Also, the nodes are not necessarily connected by only one linking mechanism. Between any two points on the network there may exist not only multiple paths of transmission, but also multiple media of transmission.

A. PURPOSE OF TRANSMISSION MEDIA

From open-wire and twisted-pair cable (also called paired cables) to microwave and wave guide transmission, the purpose of the media is to accommodate the traffic demand between any two points on the PSN. Not unlike the U.S. highway system, the PSN media is designed to carry the load of traffic. In rural, less populous areas, the simple 2-lane road suffices to link the neighboring communities. In the PSN, the rural areas may be linked by original technology, open-wire configurations. If a traveler leaves the rural area to areas of higher population density he is met by newer technology highway engineering-the freeway system. Likewise, in the PSN, areas of greater density are served by modern technology in the form of coaxial cable and optical fibers.

As better, wider, paved roads are constructed between growing rural areas, so are telecommunications media improving. The old style, open-wire may be replaced by

coaxial cable, fiber optics, microwave, or wave guide transmission systems.

B. SIGNALS THROUGH THE MEDIA

There are four (4) basic types of signals which are transmitted via the PSN media. They include:

(1) Speech,

(2) Digital Data,

(3) Video, and

(4) Program

Speech, the most common signal type, takes the form of an electrical analog acoustical wave which is created by the user's voice. The typical voice bandwidth provided by the PSN ranges from 200 to 3500 Hz with amplitude peaks at about 500 Hz. The speech signal is highly variable with regard to time, as no person can speak continuously, uninterrupted for an entire telephone conversation. The speech signal is characterized over the time quantum by periods of high activity and frequent short silent periods.

Digital data usually is composed of binary pulse trains that represent information being communicated between man-and-machine or machine-and-machine. The transmission pulse may be either synchronous, where pulses of a maximum time length are allowed or asynchronous, where the pulse's time spans are variable. For both modes there is a maximum rate which can be allowed for the PSN bandwidth of a particular channel. To standardize the digital signals, the signals are usually modulated at the origin to conform to bandwidth restrictions and demodulated at the destination, to reconstruct the origin's intended signal. The equipment used for this modulating and demodulating is the MODEM.

Video signals carried over the PSN include television and PICTUREVISION (a service which combines telephone voice and television video). Video signals are converted to electrical signals (suitable for transmission) by electronic

scanning devices. Pieces of picture are scanned, converted to signals, transmitted, and recomposed at the destination.

The last form of signal carried by the PSN is the program. This form includes radio broadcasts, music, and the audio portion of television programming. Because of the increased frequency of music over voice, the PSN can provide a frequency width of 100 to 5000 Hz. Some trunks can also provide increased bandwidths for program transmission with ranges of 50 to 8000 Hz and 50 to 15000 Hz. The program audio signals differ from speech signals in one more important aspect. They are usually one-way signals and usually transmitted over one-way channels. [Ref. 11]

C. CHANNELS

A channel is simply defined as a path which is dedicated to provide communication between two points. The channel can have either analog or digital characteristics. The digital channel operates on a sequence of time slots. The analog channel uses frequency slots. Some other type channels are combinations of frequency and time slots.

Channels are further characterized by bandwidth. The narrowband channels are between 100 and 200 Hz wide and are used for telegraph and low-speed data communication. 4 kHz voiceband channels are used for higher speed (9600 bits / second) data transmission. 48 kHz and 240 kHz channels are used for high-speed data transmission.

All channels in the PSN are either voice frequency or carrier transmission types. The voice frequency type operates so that both parties' transmission are carried on the same wire pair. This 2-wire arrangement is commonly found in loops and short trunks between central offices. Calls between area subscribers are handled through central and tandem offices over 2-wire loops. If a call needs to go outside the central office area it is routed to a toll office. The toll offices are usually connected by a 4-wire

arrangement. The toll office is connected to toll trunks by a 4-wire terminating set which splits apart the two directions of transmission to allow long-haul transmission. Figure 4.1 shows the 2-wire and 4-wire concept. [Ref. 12]

The carrier channels are a broadband system that uses the 4-wire transmission concept. The carrier system consists of three (3) functioning parts:

(1) High-frequency line equipment for broadband channels to permit simultaneous transmission of many communication signals.

(2) Modulating equipment which converts signals from their original form to a form suitable for PSN high-frequency channels.

(3) Multiplexing equipment to regulate system input and separate system output. [Ref. 13]

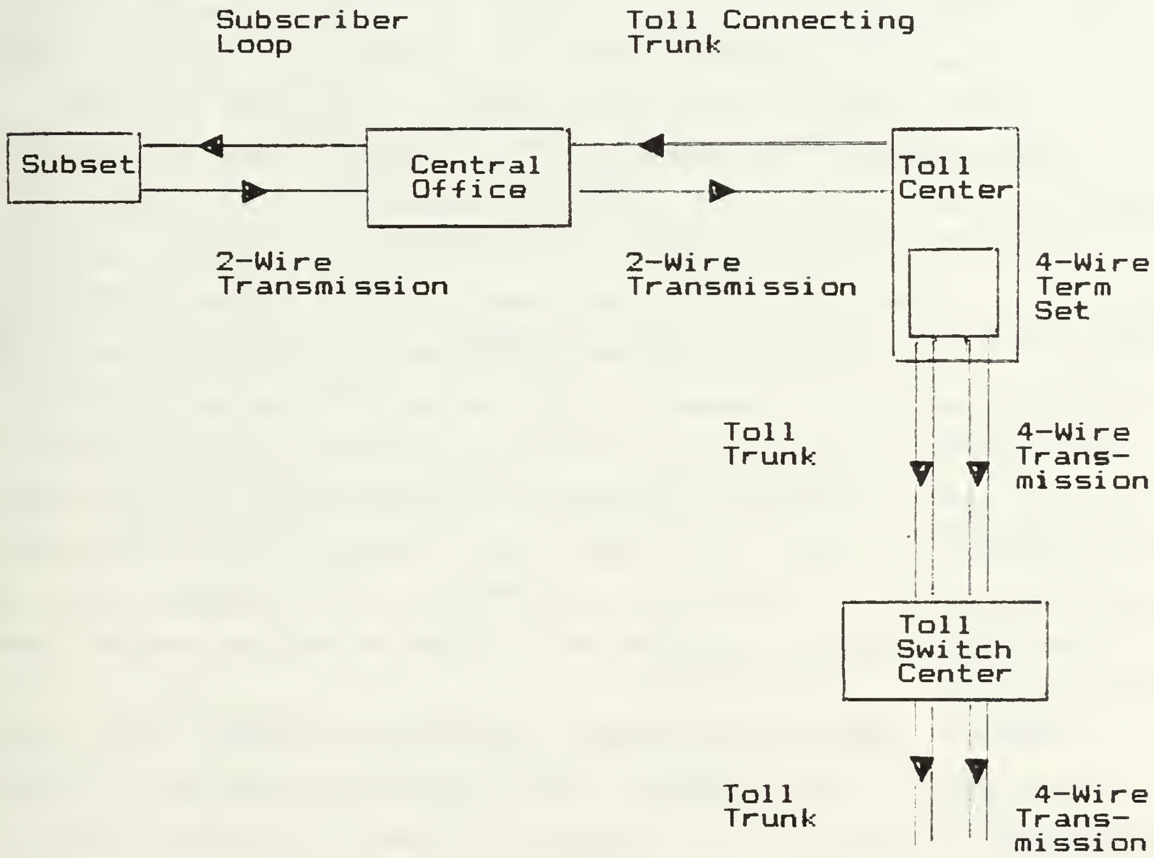


Figure 4.1 2-Wire and 4-Wire Methods of Operation

D. TELECOMMUNICATION MEDIA

The six (6) principal types of media used for loops and trunks in the PSN include the following:

(1) Open-wire lines

(2) Paired Cable (Twisted-pair)

(3) Coaxial Cable

(4) Radio (Microwave, Satellite, Terrestrial)

(5) Wave guide

(6) Fiber Optics

Open-wire lines are pairs of uninsulated, exposed wire strung on poles. Up to 50 pairs of wires may be mounted on a group of ten cross-arms on a telephone pole. The wire used is either copper, copper-clad steel, or galvanized steel. Open-wire configurations are still used in some rural areas but are being replaced by cable due to the high cost of maintenance necessary because of weather damage.

Paired-cable (twisted pair) is a media used to accommodate higher density population centers. The wires are copper or aluminum which are sheathed in wood pulp or plastic. The pairs are then combined with others in groups from 6 to 2700 pairs. These groups are again sheathed with plastic, aluminum, steel, lead, or a combination of these. Paired-cable groups may be strung on poles, buried directly, or enclosed in conduit and buried underground. Paired-cable is typically used in loop and central office/exchange configurations. Up to 12 telephone conversations may be transmitted over a single pair of wires using pulse code modulation.

Coaxial cable is the same type cable as used for cable television. The single cable consists of an inside conductor made of a thin copper wire and an outside conductor of copper tape which encircles the inner wire. The cables are combined to form groups of 8 to 22 cables which are sheathed around standard twisted-pair lines to provide even greater capacity. Figure 4.2 shows a cross-section of

coaxial and paired cable. The coaxial cable is capable of providing a bandwidth up to 8 mHz. [Ref. 14]

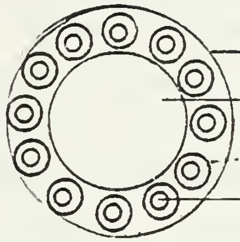


Figure 4.2 Coaxial Cable Cross-section

Radio transmission of telecommunication signals enables the PSN to span natural barriers such as lakes, mountains, and forests where buried cable would be impractical to install. This medium however, is unprotected (easily intercepted) and is limited in length by transmitter power, path length, antenna patterns, and obstructions. [Ref. 15]

The radio wave is not a single frequency, but is a bandwidth. The Federal Communications Commission (FCC) has designated the radio bandwidths according to frequency range. The various bandwidth characteristics are shown in Figure 4.3. [Ref. 16]

Band Number	Frequency Range	Frequency Name	Approx Transmission Distance	Main Uses
1	10-30kHz	VLF	>1000 mi	Military Maritime
2	30-300kHz	LF	up to 1000 mi	"
3	300-3000kHz	MF	0-1000 mi	Maritime & Broadcast
4	3-30mHz	HF	worldwide	All Services
5	30-300mHz	VHF	Slightly beyond horizon	Point-to-Point bcst
6	300-3000mHz	UHF	Horizon up to 200 mi	TV Bcst
7	3 to 30gHz	SHF	Horizon	Point-to-Point Microwave
8	> 30gHz	EHF	Horizon	Broadband Wave guide

kHz=1000 hertz/mHz=1,000,000 hertz/gHz=1000 mHz

Figure 4.3 Frequency Bands and Characteristics

Microwave radio transmitters used for terrestrial radio communication in the PSN operate between 3,000 and 12,000 mHz or 3 to 12 gHz. The microwave architecture spaces repeaters between 25 and 30 miles apart. The repeaters receive the signals, amplify them, and send them along the path. There are 64 carriers available in each direction of microwave transmission. Each carrier is capable of handling up to 2700 telephone channels. [Ref. 17]

Wave guide transmission has great potential for telecommunications over long distances because of the wide bandwidth and high-frequency carriers used. The wave guide unit can transmit 100 carriers, each handling up to 2000 telephone channels. The wave guide will operate at the 40-110 gHz range. With telephony, the higher the frequency, the more telephone channels it can carry. [Ref. 18]

Optical fibers were not considered a practical medium until the late 1960's. The fiber is actually two coaxial transparent sleeves of glass surrounded by a light-absorbing jacket. The fiber optics architecture is capable of handling both analog and digital transmissions. Optical fiber technology is expected to replace conventional wire intraoffice interconnections, medium-capacity interoffice trunks, and large-capacity intercity trunks. As lower signal-loss fibers and connections are developed, the PSN will rapidly replace present wire configurations. [Ref. 19]

E. SUMMARY

The various modes of transmission, the telecommunication media provide the second form of redundancy in the PSN. The first form of redundancy, that of multiple trunk routes between class offices, coupled with this multi-media concept enables the switched network to increase its survivability in a NETS scenario. Communication between two nodes in the

system may be accomplished via a complex of various routes (as presented in Chapter III) and various media (this chapter).

The next chapter will develop the NETS model of links and nodes, with the basis of the development as discussed in the first four chapters of this study.

V. THE NETS MODEL AND PATH ANALYSIS

The NETS model in this study will be represented by a set of nodes (hierarchical offices) and links (trunks connecting the offices). In a NETS scenario, after a disaster, the PSN user will be faced with a degraded network. The disaster may affect the network in many ways, by destroying or disabling switching offices, by damaging trunks between offices, by rendering certain types of telecommunication media useless, or by any combination of the above.

This study will assume that one of the worst types of disasters has affected the network in the continental United States. The disaster is nationwide destruction of major population/industrial centers as a result of declared war. As these centers are prime targets for hostile forces in war, the PSN is likely to suffer major damage to several (if not all) upper level hierarchical offices (class 1 and 2, the sectional and regional offices). With the loss of these nodes, severe limitations will be placed upon the PSN to complete crucial communications between two end users of the network in different regions of the country. The redundancy of routing, through multiple land line paths and multiple media types between various class offices can allow the PSN to maintain nationwide communications.

A. ASSUMPTIONS AND CONSTRAINTS OF THE MODEL

To limit the study of redundancy routing in the PSN to a manageable scope the author makes the following assumptions and constraints:

(1) Telecommunications on the PSN will consist of class 3, 4, and 5 hierarchical offices only. It assumes that class 1 and 2 offices and those class 3, 4, and 5 offices in the vicinity of class 1 and 2 offices will be disabled.

(2) Telecommunications will be completed in the PSN through remaining class 3,4, and 5 offices in a typical hierarchical fashion. Figure 5.1 illustrates

the model architecture. The model phone call will originate at an end user and be routed up the hierarchy of offices serving the origin; the call will then travel over a primary trunk to the destination hierarchy of class 3, 4, and 5 offices to the destination user in the following general manner: 5-4-3-3-4-5.

(3) Routing of traffic will flow up the office hierarchy at the origin and down the office hierarchy of the destination. The possible routing sequences (referring to figure 5.1) are: 5-4-3-3-4-5, 5-4-3 (origin)-4-5, 5-4-3 (destination)-4-5, or 5-4-4-5.

(4) The routing of traffic will pass through a node (office) only once (i.e., traffic will not be looped back through a node once it has passed through the first time).

(5) The links of the NETS model are confined to the more conventional media of paired cable, coaxial cable, and microwave. Capacities of each of the media types will vary and the effects of the capacities on the model will be studied later.

(6) Trunk traffic in the PSN will be limited due to congestion and subject to restrictions by a precedence authority.

(7) The maximum number of subordinate offices for one primary (class 3) office is: 3 toll (class 4) offices and 9 central (class 5) offices. These office ratios are in concert with the types and quantities listed in Chapter III. Figure 5.2 shows these relationships. The impact of tandem offices at the class 5 level will be examined, as will the effects of dual trunks between adjacent offices in Chapter VI.

(8) The object of the model is to complete a phone call, for voice or data communications, from one end user in one primary center's domain to an end user in an adjacent primary center's domain. To study more than two primary centers at a time would be repetitious and add unnecessarily to the model complexity. The research presented can be extended to apply to more complex scenarios involving more than 2 primary centers, as desired.

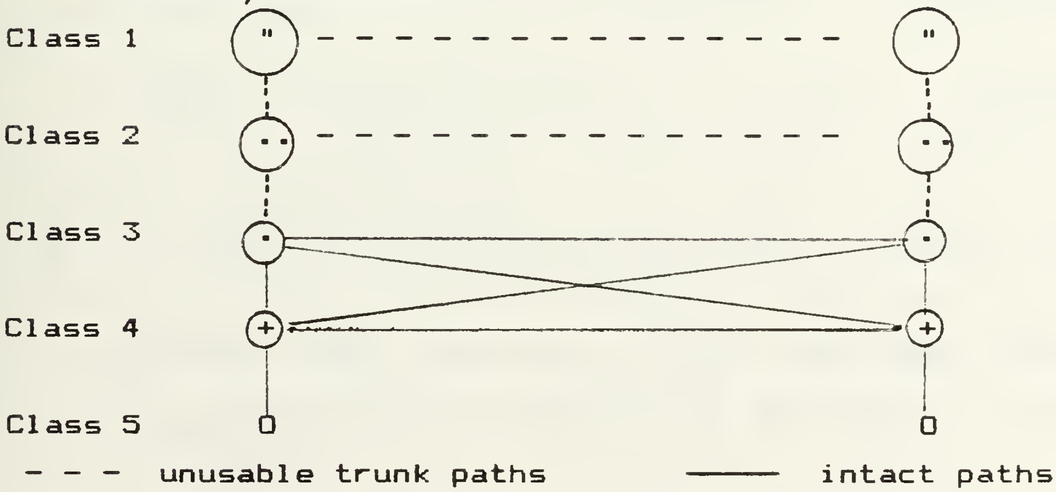
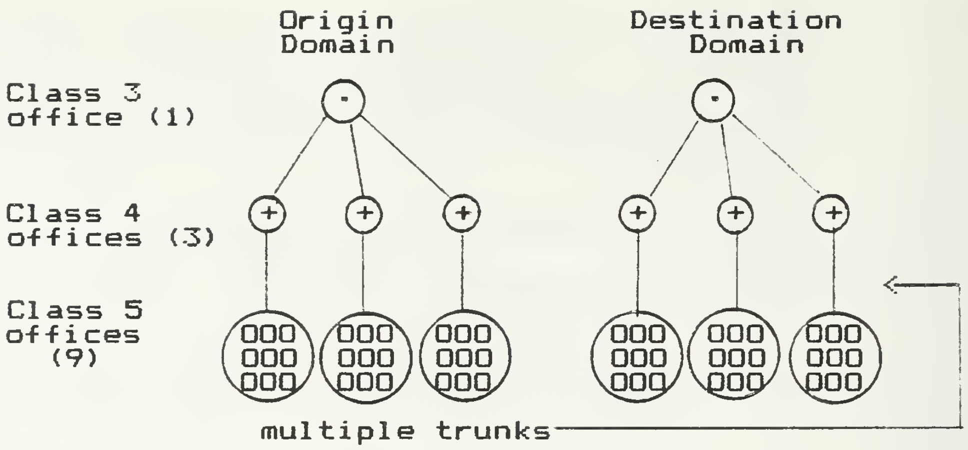


Figure 5.1 NETS Model Traffic Routing



(nn) indicates quantity limit per primary area

Figure 5.2 NETS Scenario Office Configuration Limits

B. MODEL DEVELOPMENT THROUGH PATH ANALYSIS

To examine redundant routing in the form of multiple paths between two end users it is helpful to provide a basic structure from which to expand. Figure 5.3 depicts the basic net architecture to initiate PSN path analysis (examining all the routes between origin and destination). A convention to be used throughout this chapter follows. The origin will always be a class 5 office. This office will be labelled number 1. The destination will always be the highest number in the sequence shown. For example, in Figure 5.3, label 1 is the origin and label 14 is the destination.

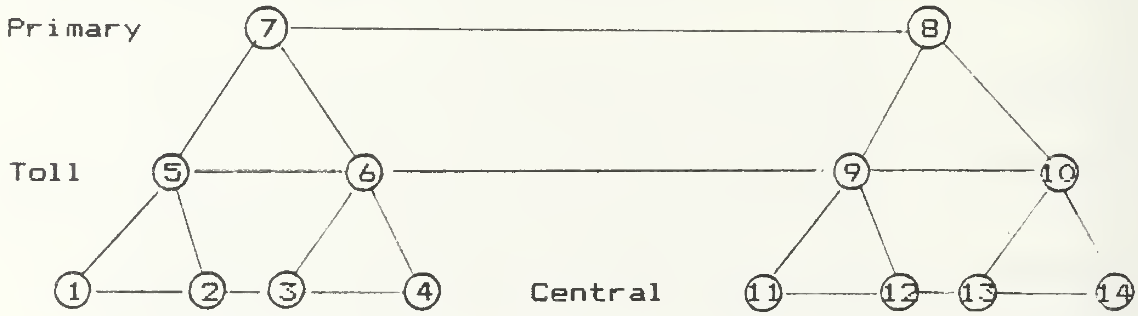


Figure 5.3 Basic Path Analysis Architecture

When conducting path analysis of a subset of the NETS model a similar convention holds. Label 1 will be the origin and the highest number shown denotes the immediate destination. For example, if studying an architecture consisting of one toll office and three central offices, labels 1, 2, and 3 would indicate central offices and label 4 would denote the toll office (the immediate destination, in this case). Figure 5.4 illustrates this convention.

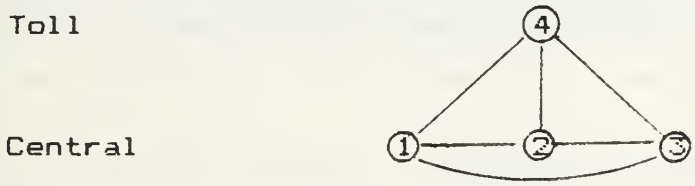


Figure 5.4 Example Subset Path Analysis

1. <u>Path Analysis Definitions</u>

TOTAL CONNECTIVITY--a condition that exists in a subset network where all nodes contain links to each of the other nodes.

TOTALLY CONNECTED GROUP--a group of nodes which exhibit total connectivity. In Figure 5.3, 5-6-7 is a totally connected group.

PARTIAL CONNECTIVITY--a condition that exists when all of the nodes in a network subset are not connected to each other.

PARTIALLY CONNECTED GROUP--a group of nodes which exhibit partial connectivity. In Figure 5.3, 1-2-3-4-5-6 is a partially connected group.

ULTIMATE DESTINATION--the node in the network which is the office that serves the destination FSN user.

IMMEDIATE DESTINATION--the node in the network which serves as the temporary destination of the call in a subset analysis situation.

PATH--a link (trunk) or set of links which connects the group of nodes under study. A numerical sequence, such as 12345 defines the order of path execution through nodes 1, 2, 3, 4, and 5.

UNIQUE PATH--a path that consists of a unique set and sequence of nodes. In a network consisting of 3 central offices and 1 toll office the paths 12345 and 12435 are unique paths from origin 1 and immediate destination 5. Redundant routes are formed by multiple unique paths.

TOLL FAMILY--a group of central offices and its servicing toll office. In Figure 5.3, 1-2-5 is a toll family.

PRIMARY FAMILY--a group of central offices and toll offices and their servicing primary office. In Figure 5.3, 1-2-3-4-5-6-7 is a primary family.

TANDEM FAMILY--a group of central offices and its servicing tandem office.

CLASS 3/4 LINK--a link which connects two unrelated (non-family) nodes. The link may connect a primary to primary, toll to primary, primary to toll, or toll to toll. Each end point of the link is in an adjacent primary domain. In Figure 5.3 the links 78, 68, 79, and 69 are class 4/5 links.

2. Path Analysis By Inspection

One way to achieve redundancy in the PSN is through total connectivity. In Figure 5.5 redundancy is determined by inspection. Count the paths between 1 (the origin) and 7 (the ultimate destination). The inspection yields two unique paths: 134567 and 1234567. If another class 5 office at the destination is added along with a local loop between the destination class 5 offices (for total connectivity) four unique paths are achieved. Figure 5.6 shows this structure. By inspection again, the unique paths between 1 (the origin) and 8 (the destination) are found. The paths are 134568, 1234568, 1345678, and 12345678. As more nodes

are added, determining unique paths by inspection becomes more difficult.

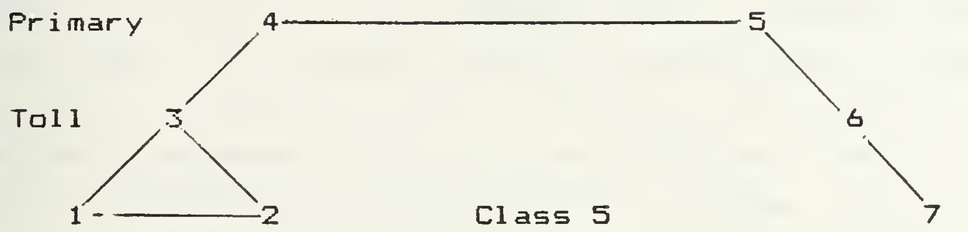


Figure 5.5 Unique Path Determination By Inspection
Two unique paths

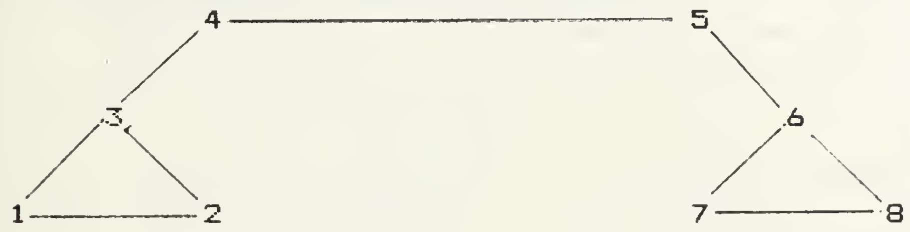


Figure 5.6 Unique Path Determination By Inspection
Four unique paths

The remainder of this chapter is devoted to the development of an algorithm for determining unique paths in a NETS scenario. The approach begins with examination of toll families and extends with the incorporation of more complex structures, including tandem offices (at level 5) and class 3/4 links.

C. ORIGIN TOLL FAMILY PATH ANALYSIS

To conduct path analysis in the PSN, it is easiest to begin by examining toll family structures. This section of the chapter will be confined to path analysis between one toll (class 4) office and from 1 to 10 subordinate central offices (class 5). The purpose of this section is to determine the unique path sequences and unique path quantities for various toll family architectures.

In the illustrations, Figures 5.7 through 5.15, the labelling convention discussed earlier for office labelling is used. That is, "1" labels the origin class 5 office and the largest number (in this section "2" - "10") indicates the immediate destination. Path analysis for the NETS scenario dictates that the first node in a path always be labelled "1" and the last node in a path always be labelled with the largest number. In this section of the study, the immediate destination will always be the toll office.

Figures 5.7 through 5.11 are self explanatory and indicate the number of unique paths and their sequencing. These PSN structures are considered "basic" as the unique paths may be determined by inspection.

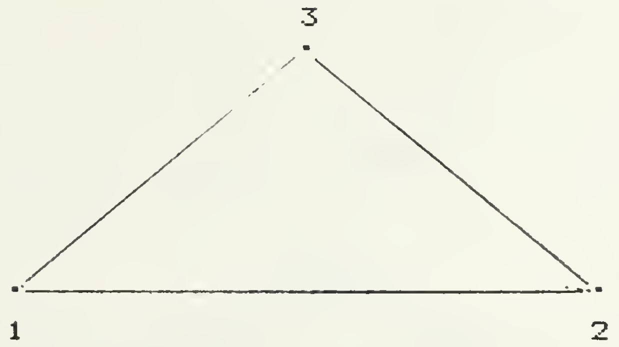
1 = Class 5 office   2 = Class 4 office

Total number of unique paths between 1 and 2 = 1

1 TWO-node path is: 12

Figure 5.7 Total Connectivity for Two Nodes

1,2 =Class 5 offices   3 = Class 4 office



Total number of unique paths between 1 and 3 = 2

1 TWO-node path is: 13

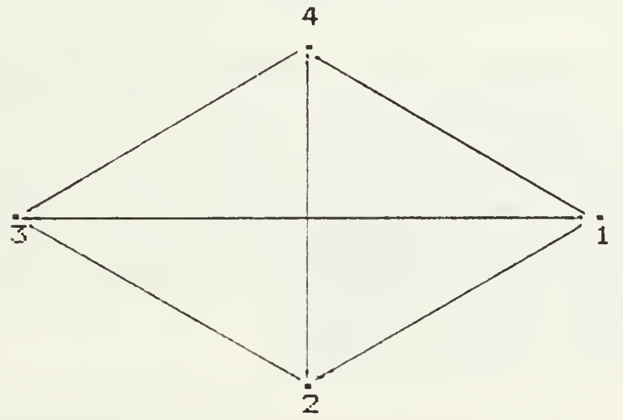
1 THREE-node path is: 123

---

2 Total paths

Figure 5.8 Total Connectivity for Three Nodes

1,2,3 = Class 5 offices   4 = Class 4 office



Total number of unique paths between 1 and 4 = 5

1 TWO-node path is: 14

2 THREE-node paths are: 124/134

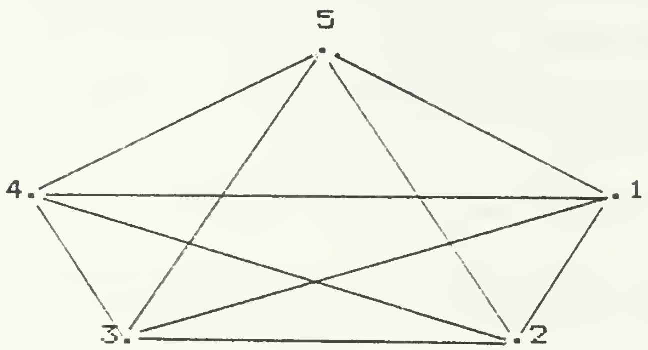
2 FOUR-node paths are: 1234/1324

---

5 Total paths

Figure 5.9 Total Connectivity for Four Nodes

1,2,3,4 = Class 5 offices 5 = Class 4 office



Total number of unique paths between 1 and 5 = 16

1 TWO-node path is: 15

3 THREE-node paths are: 125/135/145

6 FOUR-node paths are: 1235/1245/1325/1345/1425/1435

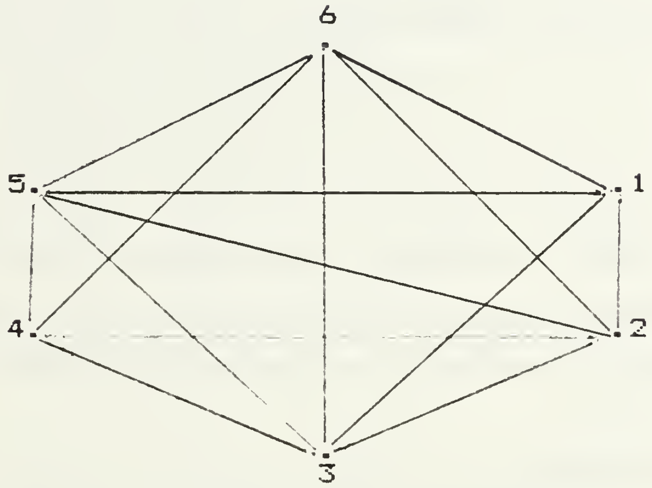
6 FIVE-node paths are: 12345/12435/13245/13425/14235/14325

---

16 Total paths

Figure 5.10 Total Connectivity for Five Nodes

1,2,3,4,5 = Class 5 office   6 = Class 4 office



Total number of unique paths between 1 and 6 = 65

1 TWO-node path is: 16

4 THREE-node paths are: 126/136/146/156

12 FOUR-node paths are: 1236/1246/1256/1326/1346/1356/1426/1436/1456/1526/1536/1546

24 FIVE-node paths are: 12346/12356/12436/12456/12536/12546/13246/13256/13426/13456/13526/13546/14236/14256/14326/14356/14526/14536/15236/15246/15326/15346/15426/15436

24 SIX-node paths are: 123456/123546/124356/124536/125346/125436/132456/132546/134256/134526/135246/135426/142356/142536/143256/143526/145236/145326/152346/152436/153246/153426/154236/154326

---

65 Total paths

Figure 5.11 Total Connectivity for Six Nodes

Figure 5.12 summarizes the findings of the toll family architecture of Figures 5.7 through 5.11.

Nodes in Toll family	Number of paths via "x" nodes x==> 2	3	4	5	6	Total
2	1	-	-	-	-	1
3	1	1	-	-	-	2
4	1	2	2	-	-	5
5	1	3	6	6	-	16
6	1	4	12	24	24	65

Figure 5.12 Table for Basic Toll Family Structures

Example use of the table: For a totally connected group of 4 central offices and 1 toll office there is/are:

1 TWO-node path

3 THREE-node paths

6 FOUR-node paths

6 FIVE-node paths

Total unique paths = 1 + 3 + 6 + 6 = 16

Based on the information provided in the inspection of Figures 5.7 - 5.11 and the results which are tabulated in Figure 5.12 an equation for number of unique paths in a totally connected network can be developed. Origin is always "1" and immediate destination is "N" (the largest label). Assumes only one path between any two nodes.

The equation for the study is based upon permutational studies of LaPatra [Ref. 20]. Using the restriction that the origin shall always be assigned the label "1" and the immediate destination shall always be assigned the largest label "N" the equation is derived. The permutations to be determined are calculated for all nodes except the origin and destination. Hence, N-2 nodes, at a time are considered in the equation. ${}_nP_r = n(n-1)\ (n-2)\ \ldots\ (n-r+1)$ is the general formula for the number of permutations of n things taken r at a time [Ref. 21].

EQUATION 1

N = total number of nodes in the family.

U = total number of unique paths in a totally connected group

$U = {}_{N-2}P_{N-2} + {}_{N-2}P_{N-3} + \ldots\ldots + {}_{N-2}P_{0}$

Example: Find total unique paths for 6 nodes: (N=6)

$U = {}_4P_4 + {}_4P_3 + {}_4P_2 + {}_4P_1 + {}_4P_0$

$= 24 + 24 + 12 + 4 + 1$

$= 65$

Armed with EQUATION 1 and the "basic" table (Figure 5.12), a more comprehensive table that includes any number of totally connected nodes can be provided. Figure 5.13 provides data for a network consisting of nodes where N = 2 to 10.

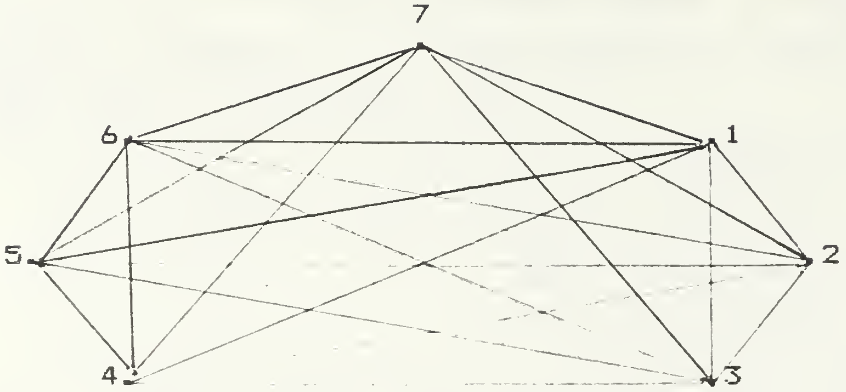
N = total number of nodes in a family
x = number of nodes that a unique path contains
U = total number of unique paths

x=> N	2	3	4	5	6	7	8	9	10	U
2	1	-	-	-	-	-	-	-	-	1
3	1	1	-	-	-	-	-	-	-	2
4	1	2	2	-	-	-	-	-	-	5
5	1	3	6	6	-	-	-	-	-	16
6	1	4	12	24	24	-	-	-	-	65
7	1	5	20	60	120	120	-	-	-	326
8	1	6	30	120	360	720	720	-	-	1957
9	1	7	42	210	840	2520	5040	5040	-	13700
10	1	8	56	336	1680	6720	20160	40320	40320	109601

Figure 5.13 Table for Complete Connectivity in Toll Families

With EQUATION 1 and the elements of Figure 5.13 graphic representations of more complex toll family structures can be provided. Figures 5.14 through 5.17 illustrate toll families of 7, 8, 9, and 10 nodes. The literal routes are not delineated as in earlier figures but quantities of the various node paths and unique path totals are provided.

1,2,3,4,5,6 = Class 5 office   7 = Class 4 office



Total number of unique paths between 1 and 7 = 326

1 TWO-node path   5 THREE-node paths

20 FOUR-node paths   60 FIVE-node paths

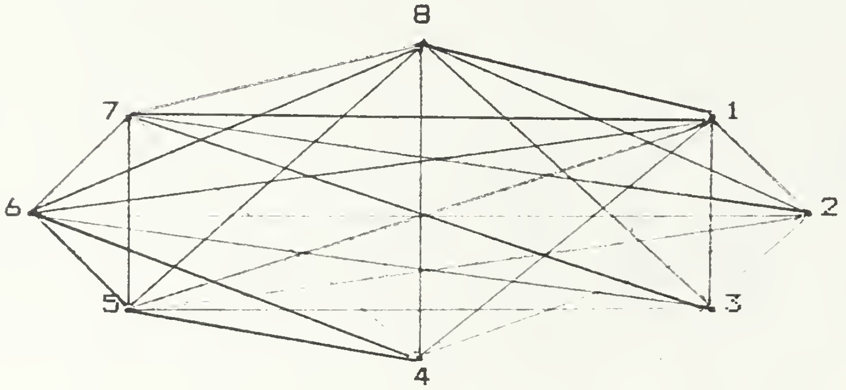
120 SIX-node paths   120 SEVEN-node paths

---

326 Total paths

Figure 5.14 Total Connectivity for Seven Nodes

1,2,3,4,5,6,7 = Class 5 office   8 = Class 4 office



Total number of paths between 1 and 8 = 1957

1 TWO-node path   6 THREE-node paths   30 FOUR-node paths

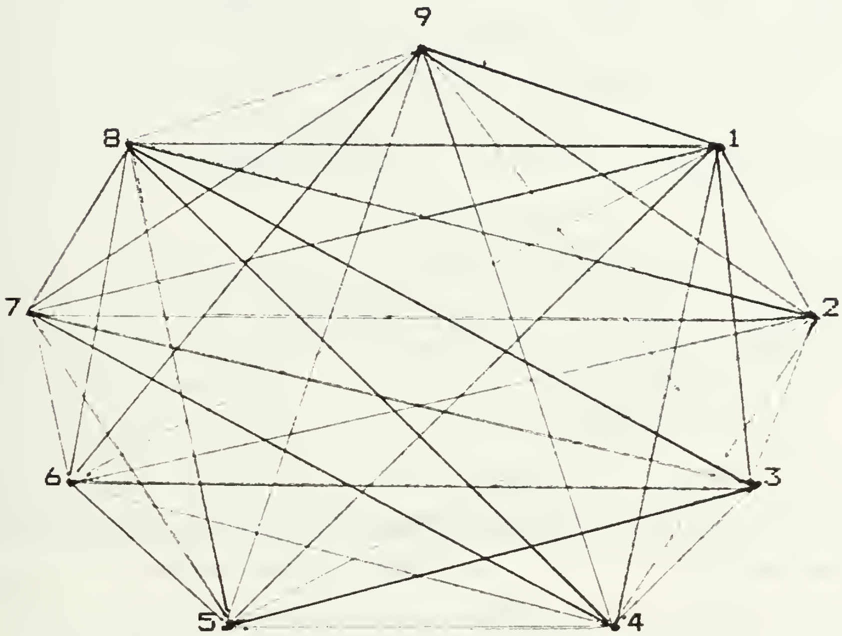
120 FIVE-node paths   360 SIX-node paths   720 SEVEN-node paths

720 EIGHT-node paths

1957 Total paths

Figure 5.15 Total Connectivity for Eight Nodes

1,2,3,4,5,6,7,8 = Class 5 office   9 = Class 4 office



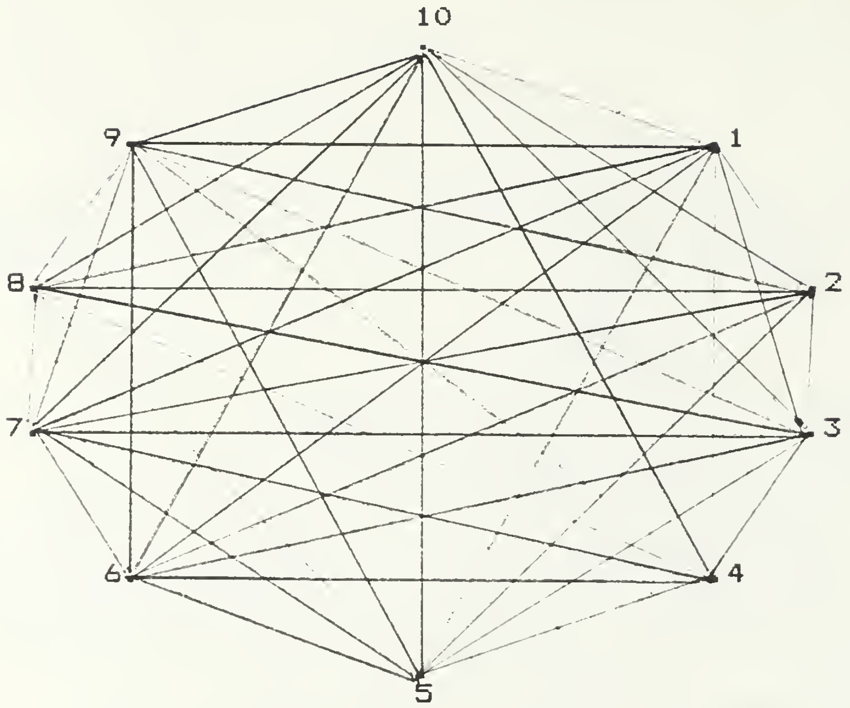
Total number of unique paths between 1 and 9 = 13,700

1 TWO-node path   7 THREE-node paths   42 FOUR-node paths
210 FIVE-node paths 840 SIX-node paths 2520 SEVEN-node paths
5040 EIGHT-node paths 5040 NINE-node paths

13700 Total paths

Figure 5.16 Total Connectivity for Nine Nodes

1,2,3,4,5,6,7,8,9 = Class 5 office   10 = Class 4 office



Total number of unique paths between 1 and 10 = 109,601

1 TWO-node path	8 THREE-node paths
56 FOUR-node paths	336 FIVE-node paths
1680 SIX-node paths	6720 SEVEN-node paths
20160 EIGHT-node paths	40320 NINE-node paths
40320 TEN-node paths	
109601 Total paths	

Figure 5.17 Total Connectivity for Ten Nodes

D. CLASS 3/4 LINK ANALYSIS

The previous section has analyzed the phone call from the origin's central office to the origin's toll office. This portion of the chapter will trace the route of the call from the origin toll office across the class 3/4 links to the destination toll office. From the origin toll office the call may be routed one of two ways, either up to the parent primary office or laterally, across to the

destination primary office domain. Figure 5.18 illustrates a typical PSN Primary domain hierarchy for class 3/4 analysis. In the figure the class 3/4 links are: 78, 68, 79, and 69. The origin, by convention, is "1" and the destination is "14".

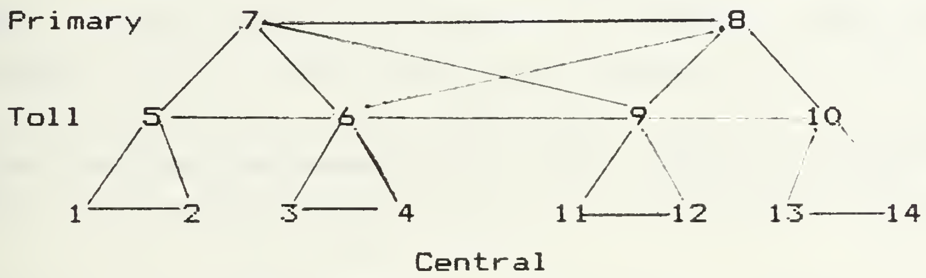


Figure 5.18 Typical PSN Hierarchy

The toll origin, in Figure 5.18 is "5" and the toll destination is "10". In this relatively simple structure it is difficult to trace all of the paths from "1" to "14". The approach used in the analysis of this routing problem is to first examine only the primary and toll offices and their trunks.

The class 4/5 analysis will be limited (as stated in the beginning of this chapter) to three toll offices and one primary office for each of the end users primary domains. some more constraints have been added in this section to make the study more manageable.

1. <u>Class 3/4 Link Analysis Constraints</u>

a. The maximum number of class 3/4 links is 9.

b. The toll/primary office design in both primary domains represent complete connectivity.

c. The origin and destination toll office nodes are not end points for the class 3/4 link unless they are without siblings (a companion toll office with the same primary parent).

2. <u>Class 3/4 Link Analysis Definitions</u>

PRIMARY-PRIMARY TRUNK (PP)--the trunk which links a primary office in the origin domain to the primary office in the destination domain.

PRIMARY-TOLL TRUNK (PT)--the trunk which links a primary office in the origin domain to the toll office in the destination domain.

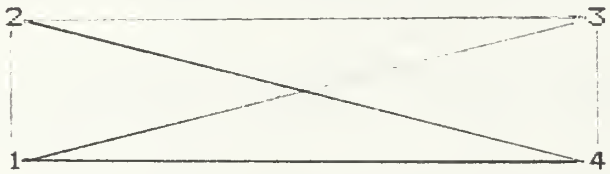
TOLL-PRIMARY TRUNK (TP)--the trunk which links a toll office in the origin domain to the primary office in the destination domain.

TOLL-TOLL TRUNK (TT)--the trunk which links a toll office in the origin domain to a toll office in the destination domain.

TRUNK PATH WEIGHT (TPW)--the number of unique paths which can be routed over any class 3/4 link (PP, PT, TP, TT).

X-Y DESIGN--a PSN structure of origin and destination primary and toll offices. The X-Y design can be a 2-2, 2-3, 2-4, 3-2, 3-3, 3-4, 4-2, 4-3, or 4-4 structure. For example, a 3-2 design is one which has 2 toll offices + 1 primary office (2 + 1 = 3) in the origin domain and 1 toll office and 1 primary office in the destination domain (1 + 1 = 2).

Figures 5.19 through 5.27 show all of the possible X-Y designs, the unique paths, and TPWs. The nodes in the lower portions of the figures are toll offices and those in the upper portion are primary offices.



Unique paths: 1234/124/134/14 = 4

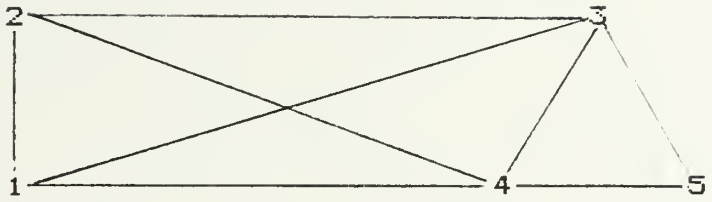
1 PP (23) with TPW = 1

1 PT (24) with TPW = 1

1 TP (13) with TPW = 1

1 TT (14) with TPW = 1

Figure 5.19 2-2 Design



Unique paths: 12345/1235/1245/1345/135/145 = 6

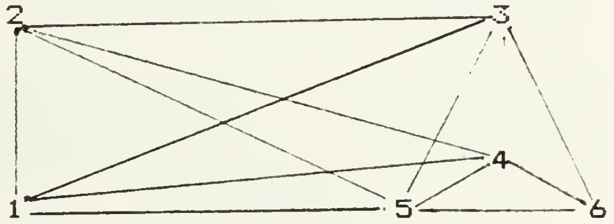
1 PP (23) with TPW = 2

1 PT (24) with TPW = 1

1 TP (13) with TPW = 2

1 TT (14) with TPW = 1

Figure 5.20 2-3 Design



Unique paths: 123456/123546/12346/12356/1236/13456/13546/
1356/1346/136/12456/1246/12546/1256/1456/146/
1546/156 = 18

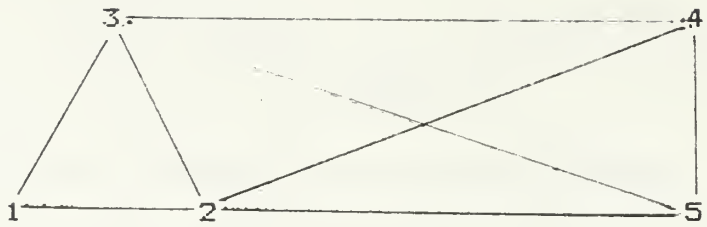
1 PP (23) with TPW = 5

2 PT (24/25) with TPW = 2

1 TP (13) with TPW = 5

2 TT (14/15) with TPW = 2

Figure 5.21 2-4 Design



Unique paths: 12345/1235/1245/125/1345/135 = 6

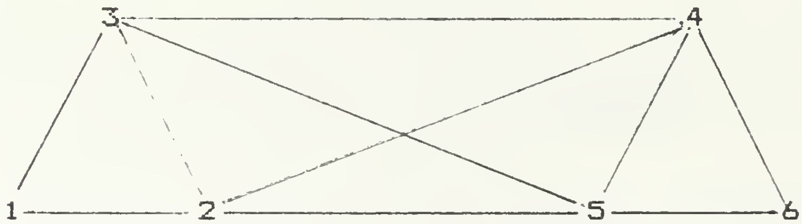
1 PP (34) with TPW = 2

1 PT (35) with TPW = 2

1 TP (24) with TPW = 1

1 TT (15) with TPW = 1

Figure 5.22 3-2 Design



Unique paths: 123456/12346/13456/1346/1356/12356/12456/
1246/1256 = 9

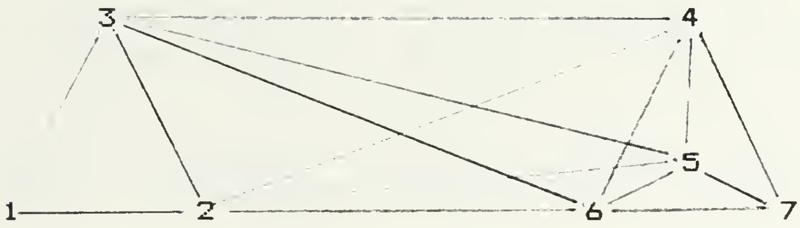
1 PP (34) with TPW = 4

1 PT (35) with TPW = 2

1 TP (24) with TPW = 2

1 TT (25) with TPW = 1

Figure 5.23 3-3 Design



Unique paths: 1234567/1234657/12347/123457/123467/134567/
134657/1347/13457/13467/124567/124657/1247/
12457/12467/123567/12357/13567/1357/123657/
123567/13657/13567/12567/1257/12657/1267 = 27

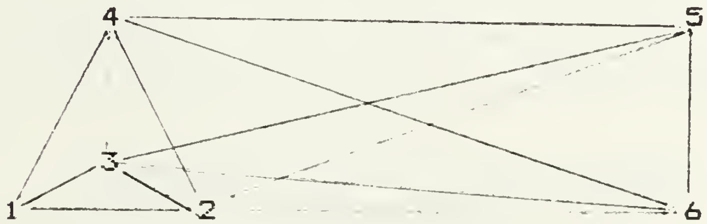
1 PP (34) with TPW = 10

2 PT (35/36) with TPW = 4

1 TP (24) with TPW = 5

2 TT (25/26) with TPW = 2

Figure 5.24 3-4 Design



Unique paths: 123456/132456/12456/1456/13456/12346/13246/
1246/146/1346/12356/1356/1236/136/1256/13256/
1326/126 = 18

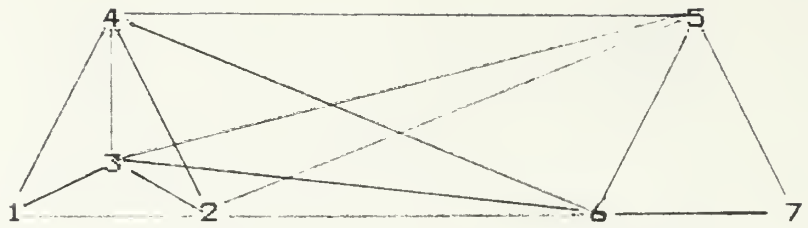
1 PP (45) with TPW = 5

1 PT (46) with TPW = 5

2 TP (25/35) with TPW = 2

2 TT (26/36) with TPW = 2

Figure 5.25 4-2 Design



Unique paths: 1234567/1324567/124567/14567/134567/123457/
132457/12457/1457/1357/123467/132467/12467/
13467/1467/123567/13567/12357/1357/12367/
1367/12567/132567/1257/13257/1267/13267 = 27

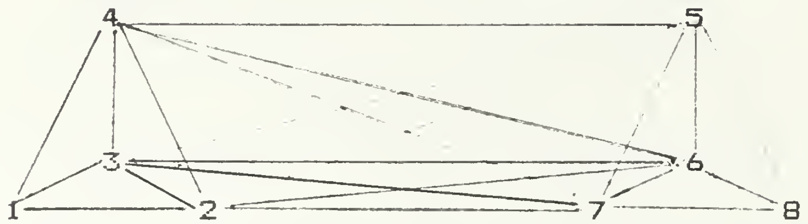
1 PP (45) with TPW = 10

1 PT (46) with TPW = 5

2 TP (25/35) with TPW = 4

2 TT (26/36) with TPW = 2

Figure 5.26 4-3 Design



Unique paths = 81

1 PP (45) with TPW = 25

2 PT (46/47) with TPW = 10

2 TP (25/35) with TPW = 10

4 TT (26/36/27/37) with TPW = 4

Figure 5.27 4-4 Design

The following two tables (Figures 5.28 and 5.29) summarize the data for the previous design figures. Figure 5.28 shows maximum number of unique paths for each design. Figure 5.29 provides a summary of the X-Y DESIGN structures and their associated TPWs.

X-Y DESIGN	MAXIMUM 3/4 LINKS	UNIQUE PATHS
2-2	4	4
2-3	4	6
2-4	6	18
3-2	4	6
3-3	4	9
3-4	6	27
4-2	6	18
4-3	6	27
4-4	9	81

Figure 5.28 Table for X-Y Design, Links and Paths

From Figures 5.19 through 5.28 and from the table in Figure 5.29 a formula can be determined for deriving the total number of unique paths over class 3/4 links in a given X-Y design.

EQUATION 2

Q = total number of unique paths

a = number of PP links b = number of PT links

c = number of TP links d = number of TT links

TPWpp = TPW for PP link TPWpt = TPW for PT link

TPWtp = TPW for TP link TPWtt = TPW for TT link

$$Q = a(TPWpp) + b(TPWpt) + c(TPWtp) + d(TPWtt) \quad \langle 2 \rangle$$

The table in Figure 5.29 reflects maximum number of each type of link, the TPW for each type and the number of unique paths (Q) for each type of X-Y design.

X-Y DESIGN	PP a(max)/TPW	PT b(max)/TPW	TP c(max)/TPW	TT d(max)/TPW	Q
2-2	1 / 1	1 / 1	1 / 1	1 / 1	4
2-3	1 / 2	1 / 1	1 / 2	1 / 1	6
2-4	1 / 5	2 / 2	1 / 5	2 / 2	18
3-2	1 / 2	1 / 2	1 / 1	1 / 1	6
3-3	1 / 4	1 / 2	1 / 2	1 / 1	9
3-4	1 / 10	2 / 4	1 / 5	2 / 2	27
4-2	1 / 5	1 / 5	2 / 2	2 / 2	18
4-3	1 / 10	1 / 5	2 / 4	2 / 2	27
4-4	1 / 25	2 / 10	2 / 10	4 / 4	81

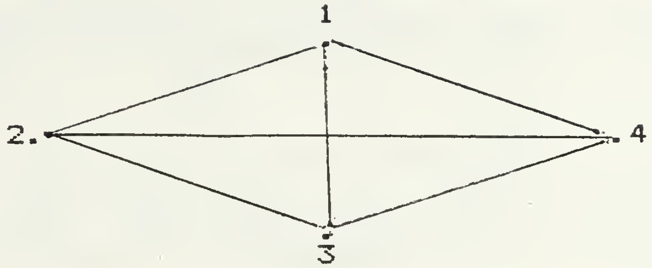
Figure 5.29   Table for X-Y Design, TPW, and Unique Paths

E. DESTINATION TOLL FAMILY PATH ANALYSIS

This portion of the chapter will examine the termination routing of the call, from the destination toll office to the destination central office. The concepts for this routing subset analysis are identical to those in TOLL FAMILY PATH ANALYSIS.

Apply EQUATION 1 and the table from Figure 5.13 to determine the number and type (via how many nodes) of paths from the destination toll office to the ultimate destination. Again, for this portion of the study, the toll family at the destination is constrained to complete connectivity. Figure 5.30 shows a destination toll family with three central offices ("2", "3", and "4") and one toll office ("1"). Label "4" is the ultimate destination central office. Its configuration is identical to Figure 5.9 (in the origin analysis).

1 = Class 4 office   2,3,4 = Class 5 offices



Total number of unique paths between 1 and 4 = 5

1 TWO-node path is: 14

2 THREE-node paths are: 124/134

2 FOUR-node paths are: 1234/1324

---

5 Total paths

Figure 5.30 Total Connectivity for Four Nodes

F. PATH SYNTHESIS

The three analyses, (1) ORIGIN TOLL FAMILY PATH ANALYSIS, (2) CLASS 3/4 LINK ANALYSIS, and (3) DESTINATION TOLL FAMILY ANALYSIS are combined in this section to study the entire path analysis, from the origin central office to the destination central office.

By determining the routing design characteristics of each of the analyses separately and then combining the characteristics algebraically one can derive the number of unique paths through an entire class 3/4/5 hierarchy. Figure 5.31 shows a typical NETS model PSN structure consisting of class 3 , 4 and, 5 offices and class 3/4 links. The origin domain contains one primary office, two toll offices, and six central offices. The destination domain has one primary office, two toll offices, and four central offices. There are four class 3/4 links (910, 911,810, and 811)

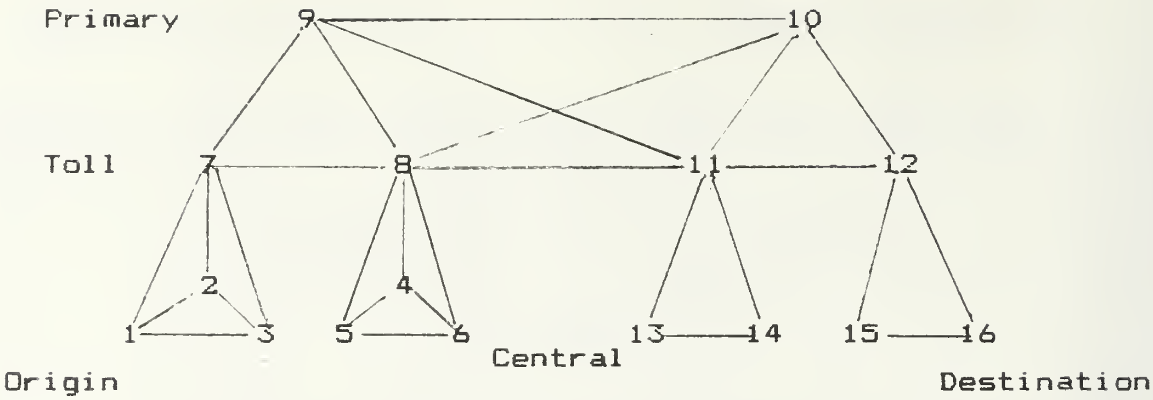


Figure 5.31 Path Synthesis Design

The final objective of this chapter is to determine the number of unique paths between the origin ("1") and the destination ("16"). The algorithm used to complete this objective follows.

Step 1: Determine the number of unique paths in origin toll family (from 1 to 7), U(O).

Step 2: Determine the number of unique paths via class 3/4 links (from origin domain to destination domain), Q.

Step 3: Determine the number of unique paths in the destination toll family (from 12 to 16), U(D).

Step 4: Determine the unique paths through the entire PSN network by EQUATION 3.

EQUATION 3

V = total number of unique paths in a class 3/4/5 PSN structure.

$$V = [U(O)] \times [Q] \times [U(D)]$$

1. <u>Path Synthesis Example</u>

Figure 5.31 serves as an example structure to step through the algorithm using the tables previously developed.

Step 1: The origin toll family is 1 toll office and 3 central offices. Referring to the table in Figure 5.13, the corresponding U value is "5", so U(O) = 5.

Step 2: The number of unique paths in a 3-3 (X-Y) design from Figure 5.29 is "9", so Q = 9.

Step 3: The destination toll family is 1 toll office and 2 central offices. In Figure 5.13, the corresponding U value is "2", so U(D) = 2.

Step 4: Using FORMULA 3, the total number of unique paths in the example can be derived. V = (5)(9)(2)= 90.

G. SUMMARY

Chapter V has developed the NETS model of a PSN structure which consists of only class 3, 4, and 5 offices. Constraints in numbers of switching offices, types of office family structures, and types of origin-destination trunks have been imposed to ease in the development of the model. A sequence of subsystem analyses, which breaks down the network into soluble partitions, has shown that the number and types of paths between nodes in the model network can be resolved. The next chapter will use the concepts of this chapter to examine the effects of multiple routing in the Public Switched Network in a NETS scenario.

VI. EFFECTS OF REDUNDANT ROUTING ON THE NETS MODEL

Chapter V developed the NETS model and formulas for the determination of unique paths through the PSN. It assumed total connectivity between origin toll family nodes and destination toll family nodes. It also represented the complete set of class 3/4 links between the origin and destination domains. This chapter will build on the basic NETS model by adding some variations to the model.

This chapter will examine in sequence: (1) partially connected groups, at the origin and destination toll family level, (2) limited class 3/4 links, (3) Class 5 tandem office structure, (4) multiple trunks between two adjacent offices, and (5) multiple media trunks between nodes and their capacities. The objective of the chapter is to derive a measure of survivability for the NETS model based on multiple media and multiple paths between the origin and destination.

A. PARTIALLY CONNECTED GROUPS

Recall from the list in Chapter V, the definition of partial connectivity--a condition that exists when all of the nodes in a network subset are not connected to each other. Figure 6.1 represents a family which is partially connected.

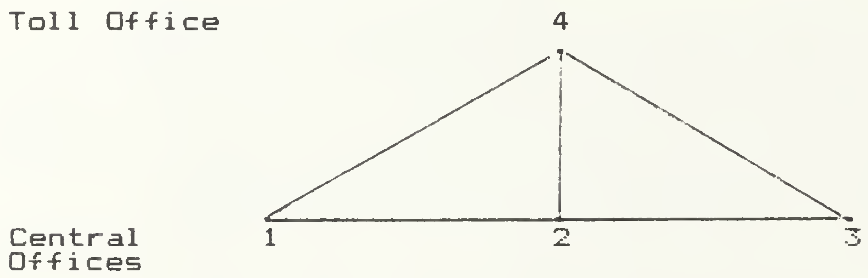


Figure 6.1 Partially Connected Toll Family

Notice that although all three class 5 offices ("1","2","3") are connected to the toll parent (4), unlike Figure 4.6 (which has 5 unique paths from 1 to 4), there are only 3 paths from "1" to "4". The missing link (1-3) causes a reduction from the optimal 5 paths to only 3 paths.

To facilitate the rest of the discussion of partial connectivity the following definitions and abbreviations will be used.

OT--A direct path defined by the origin node (O) and the toll node (T). In Figure 6.1 the OT path is 14.

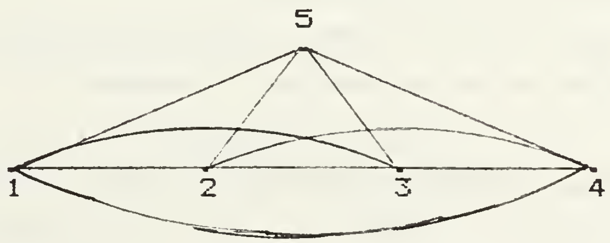
OS--A portion of a path defined by the origin node (O) and a sibling (S) node. In Figure 6.1 "2" and "3" are sibling nodes of "1" (the origin). The portion 1-2 is an OS link.

SS--A portion of a path defined by two sibling nodes. Again referring to Figure 6.1, 2-3 is an SS link.

ST--A portion of a path defined by the sibling node (S) and the toll node (T). In Figure 6.1 2-3 and 3-4 are examples of ST links.

1. Removal of One Link

To analyze the effects of the loss of links in a toll family it is easiest to start with the complete connectivity case and remove one link at a time. Figure 6.2 will be used to aid in the discussion.



Total number of unique paths between 1 and 5 = 16

1 TWO-node path: 15
3 THREE-node paths: 125/135/145
6 FOUR-node paths: 1235/1245/1325/1345/1425/1435
6 FIVE-node paths: 12345/12435/13245/13425/14235/14325

Figure 6.2 Removal of One Link Model

The toll family in Figure 6.2 shows all of the types of links. 1-5 is the OT; 1-2, 1-3, 1-4 are the OS links; 2-5, 3-5, 4-5 are the ST links; 2-3, 2-4, 3-4 are the SS links.

If the 1-5 link is deleted the loss of unique paths is one (15). The loss of the OT link in all toll family structures always results in a deletion of one unique path.

If one OS link, 1-3, is deleted the loss of paths is five (135/1325/1345/13245/13425). If any one of the OS links were deleted from this model figure the loss would be 5 paths.

If one ST link, 4-5, is deleted the loss of paths is five (145/1245/1345/12345/13245). Any one ST link deleted from the model would cause a five path reduction.

The deletion of one SS link, 2-3, results in the loss of six unique paths (1235/1325/12345/13245/14235/ 14325). For this model family the removal of only one SS link always costs six paths.

The results of only one link lost at a time in a simple toll family structure is easily determined by inspection. As the number of nodes in a family increases and as the loss of links exceeds one the analysis becomes much more complex. Figure 6.3 is a table which shows the effects of the removal of either one OS link or one ST link from toll families consisting of 2-10 nodes.

The toll family model of Figure 6.3 and the table are used to determine unique path losses. "N" = 5, in this case. Removal of OS link 1-3 results in the loss of 1 THREE-node path, 2 FOUR-node paths, and 2 FIVE-node paths. Similarly, the loss of one ST link, 4-5 causes the loss of five paths.

The results in this table were derived from a variation of EQUATION 1 from Chapter V. When a link contains either the origin (O) or the toll destination (T) as in the OS and ST links 1/(N-2) (where N = total number of nodes in

the family) will be lost when the OS or ST link is removed. The permutations for each of the type paths (i.e., THREE-node, FOUR-node etc.,) will be reduced in proportion with the total loss. EQUATIONS 4 and 5 show the losses for each type of path. [Ref. 22]

x = number of nodes that a unique path contains

N = total number of nodes in a family

T = total number of OS or ST links in architecture

N	T	x==> 3	4	5	6	7	8	9	10	TOTAL
2	0	-	-	-	-	-	-	-	-	0
3	1	1	-	-	-	-	-	-	-	1
4	2	1	1	-	-	-	-	-		2
5	3	1	2	2	-	-	-	-	-	5
6	4	1	3	6	6	-	-	-	-	16
7	5	1	4	12	24	24	-	-	-	65
8	6	1	5	20	60	120	120	-	-	326
9	7	1	6	30	120	360	720	720	-	1957
10	8	1	7	42	210	840	2520	5040	5040	13700

Figure 6.3 Table for Number of Paths Lost for One ST or OS Removal

EQUATION 4

D(OS) = total paths lost due to removal of one OS link

$$D(OS) = \frac{1}{N-2} \left({}_{N-2}P_{N-2} + {}_{N-2}P_{N-3} + \ldots + {}_{N-2}P_{1} \right) \quad \langle 4 \rangle$$

EQUATION 5

D(ST) = total paths lost due to removal of one ST link

$$D(ST) = \frac{1}{N-2} \left({}_{N-2}P_{N-2} + {}_{N-2}P_{N-3} + \ldots + {}_{N-2}P_{1} \right) \quad \langle 5 \rangle$$

The loss of unique paths due to removal of the OT link is always = 1. From EQUATION 1 of the previous chapter the OT link path permutation is defined by the term ${}_{N-2}P_{0}$. [Ref. 23]

EQUATION 6 (for removal of the OT link)

$$D(OT) = 1$$

For determining the effects of the removal of one SS link from a toll family the process becomes more complex to solve via inspection as the node family size increases. These links, when removed reduce the total number of various paths as indicated in EQUATION 7. The formula was derived in [Ref. 24]. The number of paths lost for each path type is indicated by the next equation.

EQUATION 7

$$D(SS) = \frac{2(r-1)}{(N-2)(N-3)} \left({}_{N-2}P_{N-2} + {}_{N-2}P_{N-3} + \ldots + {}_{N-2}P_{2} \right) \quad \langle 7 \rangle$$

Example Use of EQUATION 7: Given a 5-node toll family (complete connectivity) the total number of unique paths (U) = 16

Using EQUATION 1 the paths are composed of the permutations:

$${}_3P_3 + {}_3P_2 + {}_3P_1 + {}_3P_0$$

6(FIVE-node) + 6(FOUR-node) + 3(THREE-node) + 1(TWO-node)

Removing the SS link 2-3 causes reductions in the paths as follows:

$$\frac{2(3-1)}{(5-2)(5-3)} (6) + \frac{2(2-1)}{(5-2)(5-3)} (6)$$

$= 4/6\ (6) + 2/6\ (6)$

$=$ 4 (FIVE-node paths) + 2 (FOUR-node paths) removed. This results in a total reduction in unique paths of 6.

The table in Figure 6.4 shows the various path reductions and total path reductions for toll families consisting of 4 to 10 nodes.

N = number of nodes in the toll family
x = number of nodes that a unique path contains

N	x==> 4	5	6	7	8	9	10	total loss
4	2	-	-	-	-	-	-	2
5	2	4	-	-	-	-	-	6
6	2	8	12	-	-	-	-	22
7	2	12	36	48	-	-	-	98
8	2	16	72	192	240	-	-	522
9	2	20	120	480	1200	1440	-	3262
10	2	24	180	960	3600	8640	10080	23486

Figure 6.4 Table for Number of Paths Lost for One SS Removal

2. Removal of More Than One Link

When more than one link is removed from the toll family, another approach to analyzing lost paths is used. For the removal of more than one ST or OS link from the structure Figure 6.3 is used. To find the effect of multiple OS or multiple ST removals simply multiply the number of links lost by the result of ONE removal. Using the table and an example 6-node family structure (N=6), the effects from the removal of 3 ST links can be determined. The total paths lost for ONE ST deletion is 16, so the total paths lost for three ST deletions is 48 (3 X 16).

In the NETS scenario it is likely that the reduction in redundant routes between offices will be caused by the destruction (or disablement) of one or more offices in a toll family. If the origin office is lost then there are no paths to consider. Likewise, if the parent toll office is out of commission, there are no paths to consider. The loss of one sibling office in a multiple sibling family does not cause total loss of communication between the origin office and the toll office. The table in Figure 6.5 summarizes the types of toll family structures, the quantities of partial paths (OS, OT, SS, ST), the number of siblings, and the

total number of unique paths in a state of complete connectivity. The table serves to show the advantages of sibling offices.

N = total number of nodes in a family

N	OT	OS	SS	ST	SIBLINGS	TOTAL PATHS
2	1	0	0	0	0	1
3	1	1	0	1	1	2
4	1	2	1	2	2	5
5	1	3	3	3	3	16
6	1	4	6	4	4	65
7	1	5	10	5	5	326
8	1	6	15	6	6	1957
9	1	7	21	7	7	13700
10	1	8	28	8	8	109601

Figure 6.5 Toll Family Characteristics

The next set of tables (Figures 6.6 through 6.13) shows the reduction of total unique paths between the origin and toll parent as the result of sibling office losses (in complete connectivity state).

N = total number of nodes in family
x = number of nodes that a unique path contains
S = number of sibling (class 5 offices in addition to origin) offices in the family

N	S	x==> 3	4	5	6	7	8	9	10	Total lost paths
3	1	1	-	-	-	-	-	-	-	1
4	2	1	2	-	-	-	-	-	-	3
5	3	1	4	6	-	-	-	-	-	11
6	4	1	6	18	24	-	-	-	-	49
7	5	1	8	36	96	120	-	-	-	261
8	6	1	10	60	240	600	720	-	-	1631
9	7	1	12	90	480	1800	4320	5040	-	11743
10	8	1	14	126	840	4200	15120	35280	40320	95901

Figure 6.6 Path Loss Due to One Sibling Removed

N	S x==>	3	4	5	6	7	8	9	10	Total lost paths
4	2	2	2	-	-	-	-	-	-	4
5	3	2	6	6	-	-	-	-	-	14
6	4	2	10	24	24	-	-	-	-	60
7	5	2	14	54	120	120	-	-	-	310
8	6	2	18	96	336	720	720	-	-	1892
9	7	2	22	150	720	2400	5040	5040	-	13374
10	8	2	26	216	1320	5000	19440	40320	40320	106664

Figure 6.7 Path Loss Due to Two Siblings Removed

N	S x==>	3	4	5	6	7	8	9	10	Total lost paths
5	3	3	6	6	-	-	-	-	-	15
6	4	3	12	24	24	-	-	-	-	63
7	5	3	18	60	120	120	-	-	-	321
8	6	3	24	114	360	720	720	-	-	1941
9	7	3	30	186	816	2520	5040	5040	-	13635
10	8	3	36	276	1540	6600	20160	40320	40320	109275

Figure 6.8 Path Loss Due to Three Siblings Removed

N	S x==>	3	4	5	6	7	8	9	10	Total lost paths
6	4	4	12	24	24	-	-	-	-	64
7	5	4	20	60	120	120	-	-	-	324
8	6	4	28	120	360	720	720	-	-	1952
9	7	4	36	204	840	2520	5040	5040	-	13684
10	8	4	44	312	1656	6720	20160	40320	40320	109536

Figure 6.9 Path Loss Due to Four Siblings Removed

N	S	x==> 3	4	5	6	7	8	9	10	Total lost paths
7	5	5	20	60	120	120	-	-	-	325
8	6	5	30	120	360	720	720	-	-	1955
9	7	5	40	210	840	2520	5040	5040	-	13695
10	8	5	50	330	1680	6720	20160	40320	40320	109585

Figure 6.10 Path Loss Due to Five Siblings Removed

N	S	x==> 3	4	5	6	7	8	9	10	Total lost paths
8	6	6	30	120	360	720	720	-	-	1956
9	7	6	42	210	840	2520	5040	5040	-	13698
10	8	6	54	336	1680	6720	20160	40320	40320	109596

Figure 6.11 Path Loss Due to Six Siblings Removed

N	S	x==> 3	4	5	6	7	8	9	10	Total lost paths
9	7	7	42	210	840	2520	5040	5040	-	13699
10	8	7	56	336	1680	6720	20160	40320	40320	109599

Figure 6.12 Path Loss Due to Seven Siblings Removed

N	S	x==> 3	4	5	6	7	8	9	10	Total lost paths
10	8	8	56	336	1680	6720	20160	40320	40320	109600

Figure 6.13 Path Loss Due to Eight Siblings Removed

3. Summary of Partially Connected Groups

The partially connected toll family is a more appropriate representation of the switched network. The number of unique paths lost varies with the type of link (OS, ST, SS, OT) missing from the toll family.

Equations derived from EQUATION 1 of Chapter V are used to determine the number of paths lost. In most cases, the removal of a Sibling-to-Sibling (SS) link causes the greatest reduction in redundant paths for a toll family.

When nodes are removed from the toll family all of the links associated with the removed link become useless. The number of redundant paths drops drastically. The reduction in quantity of redundant paths with node removal is presented in a set of tables (Figures 6.6 through 6.13).

B. LIMITED CLASS 3/4 LINKS

Recall from Chapter V that class 3/4 links are those trunks which connect primary to primary, primary to toll, and toll to toll offices that are in adjacent primary domains. Again, in this chapter the subset study will be confined to the routing of the call from the toll origin office to the destination toll office (without concern for central offices).

Figure 6.14 is added to aid in the discussion. The table shows the maximum available class 3/4 links available for a given PSN structure of origin and destination primary and toll offices (X-Y designs). The TPWs (trunk path weights) are the number of unique paths which can be routed over the particular type of class 3/4 link (PP, PT, TP, TT).

a = max number of PP links   b = max number of PT links
c = max number of TP links   c = max number of TT links
TPWL = number of unique paths lost due to one link deletion
Q = total number of unique paths via the X-Y design

X-Y DESIGN	PP a/TPWL	PT b/TPWL	TP c/TPWL	TT d/TPWL	Q
2-2	1/1	1/1	1/1	1/1	4
2-3	1/2	1/1	1/2	1/1	6
2-4	1/5	2/2	1/5	2/2	18
3-2	1/2	1/2	1/1	1/1	6
3-3	1/4	1/2	1/2	1/1	9
3-4	1/10	2/4	1/5	2/2	27
4-2	1/5	1/5	2/2	2/2	18
4-3	1/10	1/5	2/4	2/2	27
4-4	1/25	2/10	2/10	4/4	81

Figure 6.14 Table for X-Y Design, TPWL, and Unique Paths

Figure 6.15 shows a typical PSN structure which is a 3-3 design. Each primary domain has one primary office and two toll offices. Using Figure 6.14 as a guide, the total number of unique paths between "1" (the origin toll) and "6" (the destination toll) is 9 (Q). The removal of any of the class 3/4 links (through design or destruction) reduces the total number of unique paths. The loss of the PP trunk (34) reduces the total unique paths from toll "1" to toll "6" by 4 (from 9). The lost paths are 123456/13456/ 12346/1346.

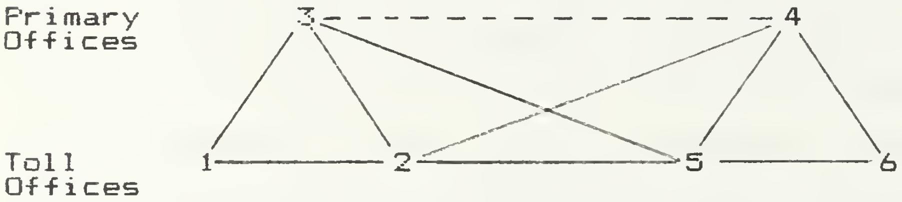


Figure 6.15 Typical PSN Class 3/4 Links and Structure

The effects of removal of various class 3/4 links on the NETS model varies with the particular type of link removed and with the particular X-Y design. These effects will be critical in the determination of a measure of survivability for the NETS model.

For any given X-Y design the loss of the Primary-to-Primary link has the greatest detrimental effect. The absence of this link through design or destruction reduces total Trunk Path Weight (Q) from 25 to 44 percent, depending on the particular X-Y design.

C. CLASS FIVE TANDEM OFFICE STRUCTURES

Recall from Chapter II the tandem office is a switch to accommodate heavy traffic between three or more central offices.

When positioned at level 5, the central office level, the tandem office becomes an important element in the NETS model. The tandem office existence becomes vital if the

call initiated at the origin class 5 office must be routed through it to the toll parent as shown in Figure 6.16.

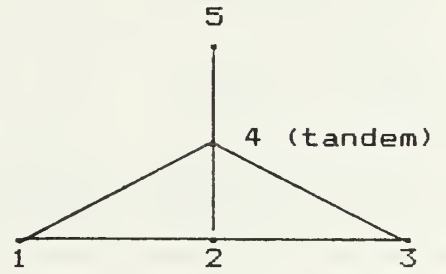


Figure 6.16 Tandem-critical Architecture

In the above case the tandem office ("4") serves the central offices by providing tandem trunks between the non-adjacent offices ("1" and "3"). More importantly, it serves the central offices as a critical node in the completion of all calls outside of the toll family. Because of its placement in this particular structure it is defined as a tandem-critical office. The three possible paths from "1" to "5" all pass through the tandem office. The paths are 145, 1245, and 12345.

Figure 6.17 illustrates a case where the tandem office, although important, is not critical. The completion of any call from the origin to the toll parent is not necessarily routed through the tandem office. Because of its placement in the toll family, it is defined as a tandem-redundant office. That is to say, that a call from the origin ("1") to the toll parent ("5") has at least two possible paths and at least one of the possible paths is not routed through the tandem office. In the figure, the tandem office provides redundant routes from the origin to the toll parent. In Figure 6.17 the paths from "1" to "5" are 15, 1235, and tandem-redundant paths: 12345, 14235, and 1435.

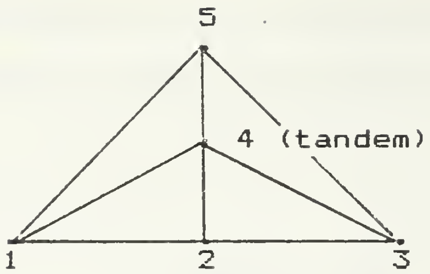


Figure 6.17 Tandem-redundant Architecture

Various other configurations of class 5 offices and tandem offices can be devised, however, in all cases the tandem office will either be tandem-critical or tandem-redundant. In the NETS scenario, the destruction of a tandem office at level 5 (if tandem-critical), will preclude any call from the origin to destinations outside of the toll family.

For toll destination family path analysis with tandem offices, the same conditions hold. If the tandem office is included on all paths from the destination toll parent to the destination central office the tandem node is tandem-critical. If at least one other path from the destination toll parent to the destination does not include the tandem node, the office is tandem-redundant.

D. DUPLICATED TRUNKS BETWEEN ADJACENT OFFICES

Consider the paths from the origin ("1") to the toll parent ("4") in Figure 6.18. The multiple trunk between the origin and the sibling ("2") has an added redundancy effect over the normal complete connectivity case.

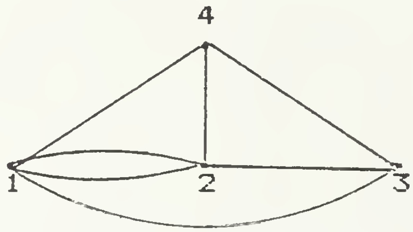


Figure 6.18 Duplicated OS Link

In the normal, single-link, complete connectivity case the five paths between "1" and "4" are: 14, 124, 134, 1234, and 1324. With the duplicated OS link (1-2) the number of paths increase to seven. The paths are the five original paths plus duplicated paths, 124 and 1234.

In Figure 6.19, the added SS link, 2-3 is shown. It doubles all paths which contain the sequence 2-3 or 3-2. The total paths increase from five to seven with the five original paths and the duplicated paths 1234 and 1324.

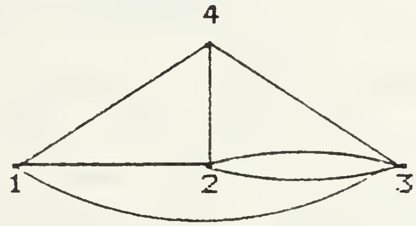


Figure 6.19 Duplicated SS Link

Figure 6.20 shows a duplicated ST link, 3-4. It doubles all paths which contain the 3-4 ST link. Again the total paths increase from five to seven. The original paths (14, 124, 134, 1234, and 1324) are complimented by duplicate paths 134 and 1234.

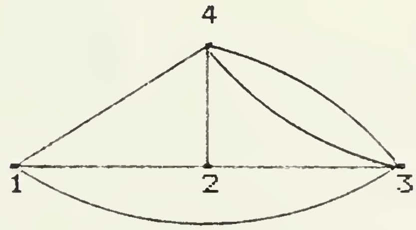


Figure 6.20 Duplicated ST Link

Using the tables from Figures 5.3 and 5.4 (the deletion tables), the additional paths gained by adding any one type of link (OT, OS, SS, ST) can be tabulated. Figure 6.21 indicates the paths gained by duplicating one existing type of link to toll family structures with N = 2 - 10.

N = total number of nodes in a toll family

N	link added==>	OT	OS	SS	ST
2		1	-	-	-
3		1	1	-	1
4		1	2	2	2
5		1	5	6	5
6		1	16	22	16
7		1	65	98	65
8		1	326	522	326
9		1	1957	3672	1957
10		1	13700	23486	13700

Figure 6.21 Paths Gained in Toll Family with One Duplicated Type Link

For multiple additions of any one type of link the table in Figure 6.21 may be used. Adding two OS links between "1" and "2" in Figure 6.18 would add 4 (2 X 2) paths to the family (2 paths per added 1-2 link). Similarly, for one added SS link (such as 8-9) in a ten node family the total paths increase by 23,486 (read from table). Two added 8-9 links would add 46,972 (2 X 23,486) paths to the family. Three added 8-9 links would add 70,458 paths to the original family.

Using EQUATIONS 1, 4, 5, 6, and 7 as a basis, equations for multiple type (OT, OS, SS, ST) links may be developed. For the addition of OT links where W = number of OT links and U = number of unique paths in a toll family:

EQUATION 8

$$U = {}_{N-2}P_{N-2} + {}_{N-2}P_{N-3} + \ldots + W({}_{N-2}P_{0}) \quad \langle 8 \rangle$$

For the addition of OS links where X = number of OS links and U = number of unique paths in a toll family:

EQUATION 9

$$U = \left[1 + \frac{X}{N-2}\right]\left[{}_{N-2}P_{N-2} + {}_{N-2}P_{N-3} + \ldots + {}_{N-2}P_{1}\right] + {}_{N-2}P_{0} \quad \langle 9 \rangle$$

For the addition of ST links where Y = number of ST links and U = number of unique paths in a toll family:

EQUATION 10

$$U = [1 + \frac{Y}{N-2}][{}_{N-2}P_{N-2} + {}_{N-2}P_{N-3} + \ldots + {}_{N-2}P_{1}] + {}_{N-2}P_{0} \quad \langle 10 \rangle$$

For the addition of SS links where Z = number of duplications for a particular SS link (i.e., the 2-3 link) added between a pair of nodes and U = number of unique paths in a toll family:

EQUATION 11

$$U = [{}_{N-2}P_{N-2} + {}_{N-2}P_{N-3} + \ldots + {}_{N-2}P_{0}]$$

$$+ [\frac{2Z(r-1)}{(N-2)(N-3)}][{}_{N-2}P_{N-2} + {}_{N-2}P_{N-3} + \ldots + {}_{N-2}P_{2}] \quad \langle 11 \rangle$$

Example use of EQUATION 11: Given a completely connected 5 node toll family determine the additional paths obtained by adding 2 additional 2-3 links.

$$U = {}_{3}P_{3} + {}_{3}P_{2} + {}_{3}P_{1} + {}_{3}P_{0} + ((4)(2)/6)[{}_{3}P_{3}] + ((4)(1)/6)[{}_{3}P_{2}]$$

$$= 6 + 6 + 3 + 1 + (8) + (4) = 28$$

The original 16 paths are:		The 6 paths added with the first 2-3 duplication are:	The 6 paths added with the second 2-3 duplication are:
15	1425	1235	1235
125	1435	1325	1325
135	12345	12345	12345
145	12435	13245	13245
1235	13245	14235	14235
1245	13425	14325	14325
1325	14235		
1345	14325		

The development of EQUATIONS 8 through 11 has shown the effects of duplication of links between nodes in the toll family. The impact of the multiple links on the completely connected family on the NETS model has added additional redundancy to the model.

E. EFFECTS OF MEDIA ON THE NETS MODEL

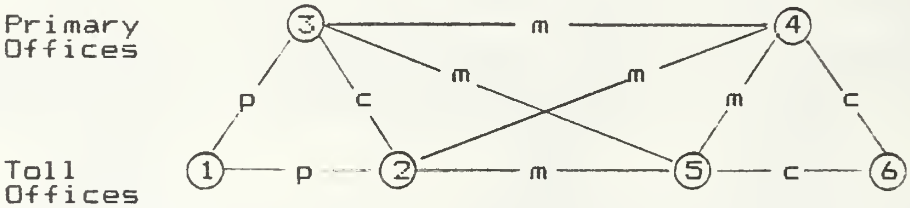
The capacities of various media has a great effect on the NETS model. Call blocking (busy line between origin and destination station) during a NETS scenario will result from

fully utilized trunks between the end users. The approximate capacities for the media constraints of the NETS model are provided in Figure 6.22. Capacities listed are those typical of long-haul trunks.

MEDIA TYPE	CAPACITY (telephone channels)
Paired cable (50 pairs at 24 channels each) [Ref. 25].	1200
Coaxial cable (10 pairs at 10,800 channels each) [Ref. 26].	108,000
Microwave (64 carriers at 2700 channels each) [Ref. 27].	172,800

Figure 6.22 Media Capacities

This NETS model will consider the effects of various media over all links outside of the toll family. In particular the links between the toll parent of the origin and the toll parent of the destination will be examined. Figure 6.23 shows a typical set of offices and trunks in the PSN hierarchy of level 3 and 4.



p = paired cable trunk c = coaxial cable trunk
m = microwave trunk

Figure 6.23 Class 3 and 4 Structure with Various Media

The figure shows the class 3/4 links and their media types. In this particular example the limiting capacity for structure is defined by the paired cable trunks at 1-2 and 1-3. For the NETS model the limiting capacity is defined as the maximum number of telephone channels available from the origin toll office to the destination toll office. The media limits the given node structure to 1200 telephone channels (the maximum channels for paired cable). The

limiting capacity shall always be the smallest amount of channels for the best path between the toll origin and the toll destination.

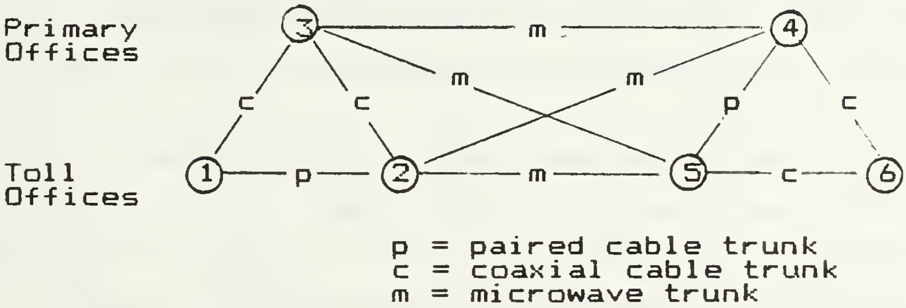


Figure 6.24 Class 3 and 4 Structure with Various Media

Figure 6.24 shows another example of limiting capacity in the class 3/4 structure. In this case the limiting capacity is defined by the 1-3 link and the 4-6 link. Although 1-2 and 4-5 are paired cable trunks (with less capacity) the best path is not defined by those links. In this case the best paths are 1356 or 1346. The limiting capacity in the figure is 108,000 channels (that of coaxial cable trunks 1-3 and 4-6).

The limiting capacity in the NETS model will be used in the next section of this chapter. This capacity will be integrated into an equation for NETS survivability.

F. A MEASURE OF SURVIVABILITY FOR THE NETS MODEL

This section of the chapter will develop a Measure of Survivability (MS) based upon redundancy of paths between the origin central office and the destination central office. This measure is designed to provide a relative degree of the capability of the NETS model to complete a call between two end users in adjacent primary domains during a NETS situation.

The previous chapter discussed the NETS model in a state of complete connectivity in the toll family and maximum class 3/4 links between primary domains. This chapter has introduced notions of partial connectivity, limited class

3/4 links, multiple links between two adjacent nodes, tandem office structure influences and limiting trunk capacities.

The approach used to develop an MS will examine each of those notions and determine Relative Measures of Survivability (RMS) for each of the categories. Specifically the RMS' to be studied are:

1. RMS for at the toll family level--RMSf
2. RMS for class 3/4 links--RMSp
3. RMS for limiting capacity on class 3/4 links--RMSc
4. RMS for influences of tandem offices--RMSt

After determining the RMS for each category an MS for a NETS model will be developed based upon an equation of the form: RM = f(RMSf, RMSp, RMSc, RMSt).

1. <u>RMS at the Toll Family--RMSf</u>

This RMS is based upon the number of unique paths at the origin and destination toll families. This chapter and the last have discussed the ways of determining the number of redundant (unique) paths between the toll parent and the origin or destination class 5 office.

Using the total possible paths in all toll family structures as an argument it is possible to assign a numeric value to the RMSf. For a two node toll family there is only one path; for a ten node toll family (in complete connectivity) there are 109,601 redundant paths. Figure 5.25 provides a table for RMSf based upon the number of redundant paths between the toll parent its serviced central office. The table will be used for determining RMSf for both origin and destination toll families.

Example use of the table: given a seven node family with one SS link missing, determine the RMSf for the structure. From Figure 6.5 the total redundant paths in a complete connectivity state for N = 7 is 326. From Figure 5.4 the lost redundant paths for one SS link removal is 98. Using Figure 6.25 and an entering argument of 228 (326-98) redundant paths, the RMSf = 6.

Number of redundant paths minimum-maximum (base value)		RMSf
0 (no paths)		0
1	(1)	1
2-3	(2)	2
4-10	(5)	3
11-40	(16)	4
41-195	(65)	5
196-1141	(326)	6
1142-7828	(1957)	7
7829-61650	(13700)	8
> 61650	(109601)	9

Figure 6.25 Table for RMSf

2. <u>RMS for Class 3/4 Links--RMSp</u>

Figure 5.29 shows various trunk path weights from 4 to 81 based upon the X-Y design of the class 3/4 structure. Figure 6.14 illustrates the effects on TPW as a result of lost or missing class 3/4 links. The limits of TPW from these two figures are 0 to 81. Figure 6.26 is the RMSp table for class 3/4 links.

Example use of table: given a 3-4 design class 3/4 structure with a missing Primary-Primary (PP) link, determine the RMSp. From Figure 6.14 with a 3-4 design, the missing PP causes a TPWL of 10. With a starting Q = 27 and subtracting the TPWL (10), the entering argument for Figure 6.26 is 17. The RMSp for TPW = 17 is 2.

Trunk Path Weight (TPW) minimum-maximum	RMSp	Trunk Path Weight (TPW) minimum-maximum	RMSp
0 (no class 3/4 links)	0	37-45	5
1-9	1	46-54	6
10-18	2	54-63	7
19-27	3	64-72	8
28-36	4	73-81	9

Figure 6.26 Table for RMSp

3. RMS for Limiting Capacity on Class 3/4 Links--RMSc

This RMS is based upon the trunk capacities of the three NETS model media (from Figure 6.22). From the capacities listed it is plain to see that the worst medium with regard to capacity is paired cable (at 1200 channels). The coaxial cable provides 90 times the capacity of paired cable and the microwave is 144 times the capacity of paired cable. The limiting capacity for any given NETS scenario is always dependent upon the smallest capacity in the best route to the destination from the origin. Accordingly, the table in Figure 6.27 shows the three proportions (ratio of media type to paired cable).

Type media	Limiting Capacity (maximum channels)	RMSc
Paired cable	1200	1
Coaxial cable	108000	90
Microwave	172800	144

Figure 6.27 Table for RMSc

4. RMS for Tandem Office Criticality--RMSt

As discussed, the tandem office at the central office level can be either critical or redundant. If it is positioned in a critical manner it has a negative effect on the survivability of the NETS model. If redundant, the tandem office has no effect on the survivability. The RMSt for a tandem-critical structure at the origin is 0.5. For a tandem-redundant structure the RMSt at the destination is assigned the value of 1. For determining the RMSt for both destination and local toll families use the table in Figure 6.28.

	Destination RMSt	
Origin RMSt	0.5	1.0
0.5	0.25	0.5
1.0	0.5	1.0

RMSt for Tandem-critical=0.5 RMSt for Tandem-redundant=1.0

Figure 6.28 Table for RMSt

5. NETS Model Measure of Survivability--MS

The RMS′ from Figures 6.25 through 6.27 may be combined in another three tables to determine an MS for a given NETS scenario. The first of the combined tables (Figure 6.29) is a matrix of the RMSf for the origin toll family and the RMSf for the destination toll family. The resultant entries are the arithmetic product of each RMSf and is denoted as RMSff.

Figure 6.30 is a composite matrix of RMSff and the class 3/4 measure, RMSp. The resultant entries again are the product of each dimension and is designated RMSfp. For the sake of space, RMSff dimensions are provided at intervals of 5.

The last table (Figure 6.31) provides the final MS calculations using RMSfp and RMSc as dimensions for the matrix. The resultant figures are the product of the entering arguments. These resultants will be summarized to form an MS for the NETS model.

	RMSf (destination)									
RMSf (origin)	0	1	2	3	4	5	6	7	8	9
0	0	0	0	0	0	0	0	0	0	0
1	0	1	2	3	4	5	6	7	8	9
2	0	2	4	6	8	10	12	14	16	18
3	0	3	6	9	12	15	18	21	24	27
4	0	4	8	12	16	20	24	28	32	36
5	0	5	10	15	20	25	30	35	40	45
6	0	6	12	18	24	30	36	42	48	54
7	0	7	14	21	28	35	42	49	56	63
8	0	8	16	24	32	40	48	56	64	72
9	0	9	18	27	36	45	54	63	72	81

Figure 6.29 Table for RMSff

RMSff	RMSp (class 3/4 links) 0	1	2	3	4	5	6	7	8	9
0	0	0	0	0	0	0	0	0	0	0
5	0	5	10	15	20	25	30	35	40	45
10	0	10	20	30	40	50	60	70	80	90
15	0	15	30	45	60	75	90	105	120	135
20	0	20	40	60	80	100	120	140	160	180
25	0	25	50	75	100	125	150	175	200	225
30	0	30	60	90	120	150	180	210	240	270
35	0	35	70	105	140	175	210	245	280	315
40	0	40	80	120	160	200	240	280	320	360
45	0	45	90	135	180	225	270	315	360	405
50	0	50	100	150	200	250	300	350	400	450
55	0	55	110	165	220	275	330	385	440	495
60	0	60	120	180	240	300	360	420	480	540
65	0	65	130	195	260	325	390	455	520	585
70	0	70	140	210	280	350	420	490	560	630
75	0	75	150	225	300	375	450	525	600	675
80	0	80	160	240	320	400	480	560	640	720

Figure 6.30 Table for RMSfp

RMSfp range	RMSc: paired cable 1	coaxial cable 90	microwave 144
1-79	1-79	90-7110	144-11316
80-159	80-159	7200-14310	11520-22896
160-239	160-239	14400-21510	23040-34416
240-319	240-319	21600-28710	34560-45936
320-399	320-399	28800-35910	46080-57456
400-479	400-479	36000-43110	57600-68976
480-559	480-559	43200-50310	69120-80496
560-639	560-639	50400-57510	80640-92016
640-719	640-719	57600-64710	92160-103536
720-729	720-729	64800-65610	103680-104976

Figure 6.31 Table for Product of RMSfp and RMSc

To determine a measure of survivability with a scale from 0 to 100 the results from the above table (Figure 6.31) for RMSfp X RMSc are divided by 1050 (assumes RMSt =1).

EQUATION 12

$$MS = \frac{[RMSf(O)][RMSf(D)][RMSp][RMSc][RMSt]}{1050} \quad \langle 12 \rangle$$

6. Measure of Survivability--An Example

Origin toll structure: 6 nodes; missing one ST link. Destination toll structure: 4 nodes; complete. Class 3/4 link structure: 3-4 design; 1 PT missing. Limiting capacity medium: coaxial cable. Tandem offices at both domains are redundant.

Methodology: Maximum number of paths for N = 6 from Figure 6.5 is 65. Paths lost due to missing ST link (Figure 6.3) are 16. Number of redundant paths in the origin toll family is 49. RMSf for 49 paths (Figure 6.25) is 5. Maximum number of paths for N = 4 (Figure 6.5) is 5. RMSf for destination is 3. Maximum TPW (Q) for 3-4 design (from Figure 6.14) is 27. TPWL from same figure for missing PT link is 2. Effective Q is 25 (27-2). RMSp (Figure 6.26) is 3. RMSc from Figure 6.27 (coaxial cable) is 90. RMSt from Figure 6.28 = 1.0.

$$MS = \frac{(5)(3)(2)(90)(1.0)}{1050} = \frac{2700}{1050} = 2.57$$

The Measure of Survivability (MS) is meant to provide a relative figure of survivability for the NETS model based on toll family path analysis, class 3/4 link analysis, and limiting media capacity.

G. SUMMARY

This portion of the thesis has presented sensitivity analysis of the NETS model. The effects of lost links, class 5 node structures, and media capacities have been addressed. Relative measures of survivability (RMS) for each

of the NETS model subsets (toll families at origin and destination, class 3/4 links, and types of trunk media) have been developed. The RMS' have been collated in an overall equation, Measure of Survivability (MS) to determine the relative capabilities of various NETS PSN structures during emergency situations.

The RMS elements of MS do not have equal weights. The most influential element is RMSc (limiting media capacity). The optimal media is microwave, followed closely by coaxial cable. The next most prominent element, RMSt, can increase or decrease MS by up to 50 percent. The tandem office, if critically positioned in the toll family, greatly reduces the MS. For NETS models with identical toll family structures and identical class 3/4 structures a difference in limiting capacity media or tandem office placement will result in diverse Measures of Survivability.

The next chapter will use all of the concepts from the last few chapters to conduct a tradeoff analysis study of the NETS model.

VII. TRADEOFF ANALYSIS: ADDED OFFICES AND ADDED TRUNKS

While Chapter V and VI addressed complete connectivity in the toll family structures, partial connectivity is more common in the PSN. This chapter will discuss partial connectivity throughout the NETS PSN structure and how to determine the number of unique paths in a partially connected network. Additionally, this section will present the tradeoffs associated with increasing survivability in the PSN.

Given any representative PSN structure, there are two ways to increase path redundancy. The first way is by adding (or duplicating) links. The second method is by adding both nodes and links to the structure.

This chapter chronology is familiar. First, it will examine the toll family structures and determine ways to increase redundancy and evaluate the tradeoffs in effectiveness with the various additions of links and nodes. The second section of the chapter will look at tradeoffs in the class 3/4 link structures. The third section covers tandem office placement and the ways to prevent tandem criticality. The results of each of the subset analyses will be collated in the final section to determine the most effective way to increase the MS (Measure of Survivability) in the NETS scenario.

This thesis will not address the economic tradeoffs associated with increasing MS, only the tradeoffs in effectiveness will be considered.

A. TOLL FAMILY TRADEOFF ANALYSIS

1. Completely Connected Toll Families

Any given toll family will either be completely connected or partially connected. If the family is

completely connected, what is the most effective way to increase redundancy ?

To answer this question one first must establish the fact that during a NETS situation any of the destination central offices has an equal likelihood of being the called office. This fact holds true for the origin office as well. That is, any central office in a toll family has the same probability of being the origin office as the other siblings in the family. If a toll family consists of "N" nodes (including the toll parent), the number of class 5 siblings is equal to N-1. The probability that any central office will be the origin (or destination) office is 1/(N-1) or p(O) = 1/(N-1) (for origin probability) and p(D) = 1/(N-1) (for destination probability). Due to these situations this chapter will not differentiate a specific origin office (or destination office), as all class 5 offices are siblings (in a given toll family).

Figure 7.1 shows a 5 node toll family. p(O) for central offices 1, 2, 3, or 4 = 1/(5-1) or 1/4.

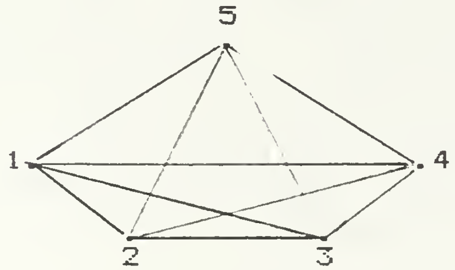


Figure 7.1 Completely Connected Toll Family

To increase redundancy in paths from the central offices to the roll parent ("5"), what is the best link to duplicate? From Figure 6.21 in the previous chapter we know that duplicating an SS link provides 6 additional paths and duplicating an ST link provides 5 additional paths. These figures hold only when the origin is known. In the case of equally likely origin, however, duplicating an SS link may

prove to be duplicating an OS link (if one of the link nodes turn out to be the origin). An OS link, in this case will only provide 5 additional paths. Also, if an ST link is duplicated, the duplicated link may turn out to be an OT link, in which case the additional redundant paths gained turns out to be only 1. To determine the Expected Redundancy Addition (ERA) for the SS link and the ST link use EQUATIONS 13 and 14 and the duplication table in Figure 6.21.

EQUATION 12

Given an N node family with p(O) for any sibling = 1/(N-1): (pass=paths added for duplicating SS link)
(past=paths added for duplicating ST link)

$$ERA\ (SS) = \frac{N-2(pass) + 1(past)}{N-1} \qquad \langle 12\rangle$$

EQUATION 13

Given an N node family with p(O) for any sibling = 1/(N-1):

$$ERA\ (ST) = \frac{N-2(past) + 1(\text{path added for duplicate OT link})}{N-1} \qquad \langle 13\rangle$$

For the example in Figure 7.1 the ERAs follow:

$$ERA\ (SS) = \frac{(5-2)(6) + 1(5)}{5-1} = \frac{23}{4} = 5.75$$

$$ERA\ (ST) = \frac{(5-2)(5) + 1}{5-1} = \frac{16}{4} = 4.00$$

For increasing redundancy (hence increasing MS) in Figure 7.1, it is optimal to duplicate one of the SS links (1-2, 1-3, 1-4, 2-3, 3-4). Figure 7.2 shows ERA (SS) and ERA (ST) in completely connected toll families for N = 3 to 10. Clearly in all cases in the table, the optimal link to duplicate is the SS link.

N	ERA (SS)	ERA (ST)
3	1	1
4	2	2
5	5.750	4
6	20.800	13
7	95.500	54.333
8	494	279.571
9	3457.625	1712.500
10	22398.667	12177.889

Figure 7.2 ERA (SS) and ERA (ST) in Complete Connectivity

The other way to increase redundancy in a completely connected toll family is to add links and nodes. Figure 7.3 summarizes the required number and types of links to bring a completely connected family of N nodes up to a completely connected family of N + 1 nodes. The figure also shows redundant paths gained and redundant paths gained per added link.

Initial N	N+1	Added SS links	Added ST links	Gain	Gain/link
2	3	1	1	1	0.500
3	4	2	1	3	1.000
4	5	3	1	11	2.750
5	6	4	1	49	9.800
6	7	5	1	261	43.500
7	8	6	1	1631	233.000
8	9	7	1	11743	1467.875
9	10	8	1	95901	10655.667

Figure 7.3 Table of Additional Links Required to Upgrade Toll Structures

2. Partially Connected Toll Families

For partially connected toll families it is again important to emphasize p(O) and p(D) = 1/(N-1). For any partially connected family any of the class 5 offices may be the origin (or destination). Because the family structure is not complete there may be any number of different links missing from the structure. The family may be missing multiple links of the same type (e.g., missing 2 SS links) or missing multiple links of different types (e.g., missing 1 ST link and 2 SS links).

As an alternative to developing numerous equations to determine existing redundant paths (before adding or duplicating links) and determining new redundant paths as a result of adding (or duplicating) links a "brute force" inspection method is offered.

Figure 7.4 presents a 4 node family with one missing ST link (3-4). If the link was missing due to design or destruction, what is the one optimum link to add (or duplicate) to achieve maximum redundancy ? Another question to ask is: what are the expected number of redundant paths gained by adding or duplicating one of the other links ?

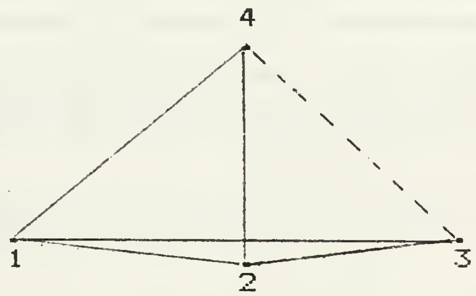


Figure 7.4 Partially Connected 4 Node Family

The way to answer these type of questions using the "brute force" method is by incorporating the following algorithm. Refer to Figure 7.5 for the algorithm mechanics.

a. Make a horizontal list of all of the links in a complete connectivity case. Delete (cross out) the missing links from the list.

b. Pick a sibling to be the origin and list all of the possible paths (in a complete connectivity case) from that origin to the toll office.

c. Delete (cross out) those paths which include the deleted link numeric sequence.

d. Examine each path with each link sequence (column) to determine the effects of duplicating the link. If a path contains the duplicated link sequence, place a star in the link column (adjacent to the path).

e. Repeat steps b, c, and d for assigning each sibling as the origin.

f. Count up the number of all single paths for each office as the origin. Add to this total the number of stars in the link column.

g. Calculate the expected number of redundant paths for the structure for each of the duplicated links using:

$$\text{Epaths} = \frac{\text{number of single paths + duplicated paths (step f)}}{N-1}$$

h. Calculate Epaths for replacing the missing link.

$$\text{Epaths} = {}_{N-2}P_{N-2} + {}_{N-2}P_{N-3} + \ldots + {}_{N-2}P_{1} + 1$$

$$\text{or Epaths} = \frac{\text{total of all paths (including deleted paths)}}{N-1}$$

To answer the original questions the Epath calculations prove that the optimal links to duplicate are: 1-4 or 2-4. By duplicating either of these links, 5 redundant paths are expected. By replacing the missing ST link, 3-4, the expected number of redundant paths is 5. If for some reason the missing link can not be installed, an equal number of expected redundant paths can be achieved with the duplication of either 1-4 or 2-4.

Figure 7.5 shows the mechanics of the algorithm with steps a-h labelled.

		12	13	23	14	24	~~34~~	
b. origin=1		included links						a.
Path								
14					*			
124		*				*		
~~134~~	c.							d.
~~1234~~	c.							
1324			*	*		*		
b. origin=2								
Path								
24						*		
214		*			*			
~~234~~	c.							d.
~~2134~~	c.							
2314			*	*	*			
b. origin=3								
Path								
~~34~~	c.							
314			*		*			
324				*		*		d.
3124		*	*			*		
3214		*		*	*			
10 paths (single)		4	4	4	5	5		f.
		(added paths from duplication)						

step g.

```
Epaths(1-2) = (10 + 4)/(4-1) = 4.667
Epaths(1-3) = (10 + 4)/(4-1) = 4.667
Epaths(2-3) = (10 + 4)/(4-1) = 4.667
Epaths(1-4) = (10 + 5)/(4-1) = 5.0
Epaths(2-4) = (10 + 5)/(4-1) = 5.0
```

step h.

```
Epaths(3-4) = (10 + 5)/(4-1) = 5.0
```

Figure 7.5 Determining Optimal Path Placement by Inspection

For dealing with multiple missing links a similar methodology is conducted. Consider the node structure in Figure 7.6. Again it is a 4 node family, but this structure is missing the SS link 1-3 and the ST link 2-4. What is the optimal duplication or replacement of links for this structure ? Again the same algorithm of defining paths and deleting paths is used (Figure 7.7).

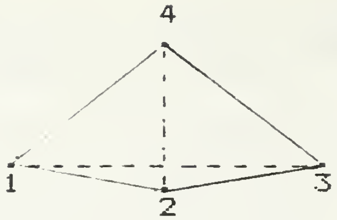


Figure 7.6 Partially connected 4 Node Family

origin=1			included links					a.
	b.	12	~~13~~	23	14	~~24~~	34	
Path								
14					*			
~~124~~	c.							
~~134~~	c.							d.
1234		*		*				
~~1324~~	c.							
origin=2								
	b.							
Path								
~~24~~	c.							
214		*			*			
234				*			*	d.
~~2134~~	c.							
~~2314~~	c.							
origin=3								
	b.							
Path								
34							*	
~~314~~	c.							
~~324~~	c.							
~~3124~~	c.							
3214		*		*	*			
----		---		---	---		---	
6 paths (single)		3 (added paths from duplication)		3	3		3	f.

step g.

Epaths(1-2)=(6+3)/(4-1)=3.0 Epaths(2-3)=(6+3)/(4-1)=3.0

Epaths(1-4)=(6+2)/(4-1)=2.667 Epaths(3-4)=(6+2)/(4-1)=2.667

step h.

$$\text{Epaths}(1-3) = \frac{(6 + \text{paths } 134,\ 2134,\ 2314 \text{ and } 314)}{4-1} = 3.333$$

$$\text{Epaths}(2-4) = \frac{(6 + \text{paths } 124,\ 24 \text{ and } 324)}{4-1} = 3.0$$

Figure 7.7 Determining Optimum Path Placement by Inspection

From this example the order of link additions or duplications may be prioritized. The choices are listed in decreasing priority:

-- Replace link 1-3
-- Replace link 2-3, or duplicate either 1-2 or 2-3
-- Duplicate either link 1-4 or link 3-4

Figures 7.8 through 7.11e2 provide tables for all of the paths for toll families with N = 3 to 6 for all origins and destinations possible. These tables are similar in format to Figures 7.5 and 7.7. These tables also provide the included links for each of the paths and may be used for partial connectivity tradeoff analysis with the previous algorithm.

LINKS OF STRUCTURE N=3

	included links		
origin=1	12	13	23
Path			
13		*	
123	*		*
origin=2	12	13	23
Path			
23			*
213	*	*	
---	---	---	---
4	2	2	2

Figure 7.8 Paths and Links for N = 3

LINKS OF STRUCTURE N=4

	included links					
origin=1	12	13	23	14	24	34
Path						
14				*		
124	*				*	
134		*				*
1234	*		*			*
1324		*	*		*	
origin=2	12	13	23	14	24	34
Path						
24					*	
214	*			*		
234			*			*
2134	*	*				*
2314		*	*	*		
origin=3	12	13	23	14	24	34
Path						
34						*
314		*		*		
324			*		*	
3124	*	*			*	
3214	*		*	*		
----	---	---	---	---	---	---
15	6	6	6	5	5	5

Figure 7.9 Paths and Links for N = 4

LINKS OF STRUCTURE N=5

origin=1 — included links

Path	12	13	14	23	24	34	15	25	35	45
15							*			
125	*							*		
135		*							*	
145			*							*
1235	*			*					*	
1245	*				*					*
1325		*		*				*		
1345		*				*				*
1425			*		*			*		
1435			*			*			*	
12345	*			*		*				*
12435	*				*	*			*	
13245		*		*	*					*
13425		*			*	*		*		
14235			*	*	*				*	
14325			*	*		*		*		

origin=2 — included links

Path	12	13	14	23	24	34	15	25	35	45
25								*		
215	*						*			
235				*					*	
245					*					*
2135	*	*							*	
2145	*		*							*
2315		*		*			*			
2345				*		*				*
2415			*		*		*			
2435					*	*			*	
21345	*	*				*				*
21435	*		*			*			*	
23145		*	*	*						*
23415			*	*		*	*			
24135		*	*		*				*	
24315		*			*	*	*			

---

continued on Figure 7.10b

Figure 7.10a Paths and Links for N = 5

origin=3 — included links

Path	12	13	14	23	24	34	15	25	35	45
35									*	
315		*					*			
325				*				*		
345						*				*
3125	*	*						*		
3145		*	*							*
3215	*			*			*			
3245				*	*					*
3415			*			*	*			
3425					*	*		*		
31245	*	*			*					*
31425		*	*		*			*		
32145	*		*	*						*
32415			*	*	*		*			
34125	*		*			*		*		
34215	*				*	*	*			

origin=4 — included links

Path	12	13	14	23	24	34	15	25	35	45
45										*
415			*				*			
425					*			*		
435						*			*	
4125	*		*					*		
4135		*	*						*	
4215	*				*		*			
4235				*	*				*	
4315		*				*	*			
4325				*		*		*		
41235	*		*	*					*	
41325		*	*	*				*		
42135	*	*			*				*	
42315		*		*	*		*			
43125	*	*				*		*		
43215	*			*		*	*			
64	22	22	22	22	22	16	16	16	16	

above totals include those from Figure 7.10a

Figure 7.10b Paths and Links for N = 5

LINKS OF STRUCTURE N=6

origin=1 included links

Path	12	13	14	15	23	24	25	34	35	45	16	26	36	46	56
16											*				
126	*											*			
136		*											*		
146			*											*	
156				*											*
1236	*				*								*		
1246	*					*								*	
1256	*						*								*
1326		*			*							*			
1346		*						*						*	
1356		*							*						*
1426			*			*						*			
1436			*					*					*		
1456			*							*					*
1526				*			*					*			
1536				*					*				*		
1546				*						*				*	
12346	*				*			*						*	
12356	*				*				*						*
12436	*					*		*					*		
12456	*					*				*					*
12536	*						*		*				*		
12546	*						*			*				*	
13246		*			*	*								*	
13256		*			*		*								*
13426		*				*		*				*			
13456		*						*		*					*
13526		*					*		*			*			
13546		*							*	*				*	
14236			*		*	*							*		
14256			*			*	*								*
14326			*		*			*				*			
14356			*					*	*						*
14526			*				*			*		*			
14536			*						*	*			*		
15236				*	*		*						*		
15246				*		*	*							*	
15326				*	*				*			*			
15346				*				*	*					*	
15426				*		*				*		*			
15436				*				*		*			*		

for subtotals see Figure 7.11a2

Figure 7.11a1 Paths and Links for N = 6 (Origin=1)

origin=1 included links

Path	12	13	14	15	23	24	25	34	35	45	16	26	36	46	56
123456	*				*			*		*					*
123546	*				*				*	*				*	
124356	*					*		*	*						*
124536	*					*			*	*			*		
125346	*						*	*	*					*	
125436	*						*	*		*			*		
132456		*			*	*				*					*
132546		*			*		*			*				*	
134256		*				*	*	*							*
134526		*					*	*		*		*			
135246		*				*	*		*					*	
135426		*				*			*	*		*			
142356			*		*	*			*						*
142536			*			*	*		*				*		
143256			*		*		*	*							*
143526			*				*	*	*			*			
145236			*		*		*			*			*		
145326			*		*				*	*		*			
152346				*	*		*	*						*	
152436				*		*	*	*					*		
153246				*	*	*			*					*	
153426				*		*		*	*			*			
154236				*	*	*				*			*		
154326				*	*			*		*		*			
------	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
65	16	16	16	16	22	22	22	22	22	22	1	16	16	16	16

Above are subtotals from Figures 7.11a1 and 7.11a2.

For totals for all origins see Figure 7.11e2.

Figure 7.11a2 Paths and Links for N = 6 (Origin=1)

origin=2	included links														
	12	13	14	15	23	24	25	34	35	45	16	26	36	46	56
Path															
26												*			
216	*										*				
236					*								*		
246						*								*	
256							*								*
2136	*	*											*		
2146	*		*											*	
2156	*			*											*
2316		*			*						*				
2346					*			*						*	
2356					*				*						*
2416			*			*					*				
2436						*		*					*		
2456						*				*					*
2516				*			*				*				
2536							*		*				*		
2546							*			*				*	
21346	*	*						*						*	
21356	*	*							*						*
21436	*		*					*					*		
21456	*		*							*					*
21536	*			*					*				*		
21546	*			*						*				*	
23146		*	*		*									*	
23156		*		*	*										*
23416			*		*			*			*				
23456					*			*		*					*
23516				*	*				*		*				
23546					*				*	*				*	
24136		*	*			*							*		
24156			*	*		*									*
24316		*				*		*			*				
24356						*		*	*						*
24516				*		*				*	*				
24536						*			*	*			*		
25136		*		*			*						*		
25146			*	*			*							*	
25316		*					*		*		*				
25346							*	*	*					*	
25416			*				*			*	*				
25436							*	*		*			*		

for subtotals see Figure 7.11b2

Figure 7.11b1 Paths and Links for N = 6 (Origin=2)

origin=2	included links														
Path	12	13	14	15	23	24	25	34	35	45	16	26	36	46	56
213456	*	*						*		*					*
213546	*	*							*	*				*	
214356	*		*					*	*						*
214536	*		*						*	*			*		
215346	*			*				*	*					*	
215436	*			*				*		*			*		
231456		*	*		*					*					*
231546		*		*	*					*				*	
234156			*	*	*			*							*
234516				*	*			*		*	*				
235146			*	*	*				*					*	
235416			*		*				*	*	*				
241356		*	*			*			*						*
241536			*	*		*			*				*		
243156		*		*		*		*							*
243516				*		*		*	*		*				
245136		*		*		*				*			*		
245316		*				*			*	*	*				
251346		*		*			*	*						*	
251436			*	*			*	*					*		
253146		*	*				*		*					*	
253416			*				*	*	*		*				
254136		*	*				*			*			*		
254316		*					*	*		*	*				
------	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
54	16	22	22	22	16	16	16	22	22	22	16	1	16	16	16

Above are subtotals from Figures 7.11b1 and 7.11b2.

For totals for all origins see Figure 7.11e2.

Figure 7.11b2 Paths and Links for N = 6 (origin=2)

origin=3 included links

Path	12	13	14	15	23	24	25	34	35	45	16	26	36	46	56
36													*		
316		*									*				
326					*							*			
346								*						*	
356									*						*
3126	*	*										*			
3146		*	*											*	
3156		*		*											*
3216	*				*						*				
3246					*	*								*	
3256					*		*								*
3416			*					*			*				
3426						*		*				*			
3456								*		*					*
3516				*					*		*				
3526							*		*			*			
3546									*	*				*	
31246	*	*				*								*	
31256	*	*					*								*
31426		*	*			*						*			
31456		*	*							*					*
31526		*		*			*					*			
31546		*		*						*				*	
32146	*		*		*									*	
32156	*			*	*										*
32416			*		*	*					*				
32456					*	*				*					*
32516				*	*		*				*				
32546					*		*			*				*	
34126	*		*					*				*			
34156			*	*				*							*
34216	*					*		*			*				
34256						*	*	*							*
34516				*				*		*	*				
34526							*	*		*		*			
35126	*			*					*			*			
35146			*	*					*					*	
35216	*						*		*		*				
35246						*	*		*					*	
35416			*						*	*	*				
35426						*			*	*		*			

for subtotals see Figure 7.11c2

Figure 7.11c1 Paths and Links for N = 6 (Origin=3)

origin=3	included links														
	12	13	14	15	23	24	25	34	35	45	16	26	36	46	56
Path															
312456	*	*				*				*					*
312546	*	*					*			*				*	
314256		*	*			*	*								*
314526		*	*				*			*		*			
315246		*		*		*	*							*	
315426		*		*		*				*		*			
321456	*		*		*					*					*
321546	*			*	*					*				*	
324156			*	*	*	*									*
324516				*	*	*				*	*				
325146			*	*	*		*							*	
325416			*		*		*			*	*				
341256	*		*				*	*							*
341526			*	*			*	*				*			
342156	*			*		*		*							*
342516				*		*	*	*			*				
345126	*			*				*		*		*			
345216	*						*	*		*	*				
351246	*			*		*			*					*	
351426			*	*		*			*			*			
352146	*		*				*		*					*	
352416			*			*	*		*		*				
354126	*		*						*	*		*			
354216	*					*			*	*	*				
------	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
65	22	16	22	22	16	22	22	16	16	22	16	16	1	16	16

Above are subtotals from Figures 7.11c1 and 7.11c2.

For totals for all origins see Figure 7.11e2.

Figure 7.11c2 Paths and Links for N =6 (Origin=3)

origin=4 — included links

Path	12	13	14	15	23	24	25	34	35	45	16	26	36	46	56
46														*	
416			*								*				
426						*						*			
436								*					*		
456										*					*
4126	*		*									*			
4136		*	*										*		
4156			*	*											*
4216	*					*					*				
4236					*	*							*		
4256						*	*								*
4316		*						*			*				
4326					*			*				*			
4356								*	*						*
4516				*						*	*				
4526							*			*		*			
4536									*	*			*		
41236	*		*		*								*		
41256	*		*				*								*
41326		*	*		*							*			
41356		*	*						*						*
41526			*	*			*					*			
41536			*	*					*				*		
42136	*	*				*							*		
42156	*			*		*									*
42316		*			*	*					*				
42356					*	*			*						*
42516				*		*	*				*				
42536						*	*		*				*		
43126	*	*						*				*			
43156		*		*				*							*
43216	*				*			*			*				
43256					*		*	*							*
43516				*				*	*		*				
43526							*	*	*			*			
45126	*			*						*		*			
45136		*		*						*			*		
45216	*						*			*	*				
45236					*		*			*			*		
45316		*							*	*	*				
45326					*				*	*		*			

for subtotals see Figure 7.11d2

Figure 7.11d1 Paths and Links for N = 6 (Origin=4)

origin=4	included links														
	12	13	14	15	23	24	25	34	35	45	16	26	36	46	56
Path															
412356	*		*		*				*						*
412536	*		*				*		*				*		
413256		*	*		*		*								*
413526		*	*				*		*			*			
415236			*	*	*		*						*		
415326			*	*	*				*			*			
421356	*	*				*			*						*
421536	*			*		*			*				*		
423156		*		*	*	*									*
423516				*	*	*			*		*				
425136		*		*		*	*						*		
425316		*				*	*		*		*				
431256	*	*					*	*							*
431526		*		*			*	*				*			
432156	*			*	*			*							*
432516				*	*		*	*			*				
435126	*			*				*	*			*			
435216	*						*	*	*		*				
451236	*			*	*					*			*		
451326		*		*	*					*		*			
452136	*	*					*			*			*		
452316		*			*		*			*	*				
453126	*	*							*	*		*			
453216	*				*				*	*	*				
------	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
65	22	22	16	22	22	16	22	16	22	16	16	16	16	1	16

Above are subtotals from Figures 7.11d1 and 7.11d2.

For totals for all origins see Figure 7.11e2.

Figure 7.11d2 Paths and Links for N = 6 (Origin=4)

origin=5	included links														
Path	12	13	14	15	23	24	25	34	35	45	16	26	36	46	56
56															*
516				*							*				
526							*					*			
536									*				*		
546										*				*	
5126	*			*								*			
5136		*		*									*		
5146			*	*										*	
5216	*						*				*				
5236					*		*						*		
5246						*	*							*	
5316		*							*		*				
5326					*				*			*			
5346								*	*					*	
5416			*							*	*				
5426						*				*		*			
5436								*		*			*		
51236	*			*	*								*		
51246	*			*		*								*	
51326		*		*	*							*			
51346		*		*				*						*	
51426			*	*		*						*			
51436			*	*				*					*		
52136	*	*					*						*		
52146	*		*				*							*	
52316		*			*		*				*				
52346					*		*	*						*	
52416			*			*	*				*				
52436						*	*	*					*		
53126	*	*							*			*			
53146		*	*						*					*	
53216	*				*				*		*				
53246					*	*			*					*	
53416			*					*	*		*				
53426						*		*	*			*			
54126	*		*							*		*			
54136		*	*							*			*		
54216	*					*				*	*				
54236					*	*				*			*		
54316		*						*		*	*				
54326					*			*		*		*			

for subtotals see Figure 7.11e2

Figure 7.11e1 Paths and Links for N = 6 (Origin=5)

origin=5 — included links

Path	12	13	14	15	23	24	25	34	35	45	16	26	36	46	56
512346	*			*	*			*						*	
512436	*			*		*		*					*		
513246		*		*	*	*								*	
513426		*		*		*		*				*			
514236			*	*	*	*							*		
514326			*	*	*			*				*			
521346	*	*					*	*						*	
521436	*		*				*	*					*		
523146		*	*		*		*							*	
523416			*		*		*	*			*				
524136		*	*			*	*						*		
524316		*				*	*	*			*				
531246	*	*				*			*					*	
531426		*	*			*			*			*			
532146	*		*		*				*					*	
532416			*		*	*			*		*				
534126	*		*					*	*			*			
534216	*					*		*	*		*				
541236	*		*		*					*			*		
541326		*	*		*					*		*			
542136	*	*				*				*			*		
542316		*			*	*				*	*				
543126	*	*						*		*		*			
543216	*				*			*		*	*				
65	22	22	22	16	22	22	16	22	16	16	16	16	16	16	1

Above are subtotals from Figures 7.11e1 and 7.11e2.

Total Paths all origins	link	12	13	14	15	23	24	25	34	35	45	16	26	36	46	56
325		98	98	98	98	98	98	98	98	98	98	65	65	65	65	65

Above are totals for all included links for all origins

Figure 7.11e2 Paths and Links for N = 6 (All Origins)

The other way to increase redundancy in the partially connected toll family is to add links and nodes. To determine the tradeoffs involved with the addition of links and nodes use the following scheme.

a. Start with the structure as it exists and add the desired links and nodes. If the completely connected model is desired, the number of redundant paths for each of the origins can be determined as discussed in Chapter V.

b. If a partially connected model is desired, the user should analyze the original structure using the algorithm in this chapter along with the tables for paths and links found in Figures 7.8 through 7.11e2. Epath calculations for each of the links should be calculated.

c. The next step is to add the desired links and nodes and again use the algorithm and tables from step b to determine the new Epath calculations.

d. Compare the Epath results from steps b and c to determine the differences in effectiveness of the two structures. Use whatever criterion is desired to decide the marginal value of the new structure as compared with the original structure and the marginal cost of the new design.

3. Summary of Toll Family Tradeoff Analysis

The previous two sections have presented the methods for determining the Expected Redundancy Additions (ERA) and the Expected Number of Redundant Paths (Epaths) for different toll family structures. The sections emphasized the equal probabilities associated with the central office being assigned as the origin or destination toll office in a NETS situation. An algorithmic inspection method and tables were provided to determine the effects of duplicating and adding links to a partially connected toll family design.

B. CLASS 3/4 LINK STRUCTURES TRADEOFFS

This section details the tradeoffs related to the adding of missing class 3/4 links or the duplication of them and for the purpose of increasing MS in the NETS scenario.

1. Complete Class 3/4 Structure Tradeoffs

A complete class 3/4 structure is one in which all of the possible class 3/4 links are in place. Figure 5.29 depicts the various X-Y designs and the maximum quantities of each type of link to make the design complete. From Figure 5.29 the reader finds the Trunk Path Weights (TPW) of each link type for each of the X-Y designs. This figure suggests the NETS maximum number of each type of class 3/4 link. Though that chapter imposed limits on the quantities of links, this section will examine the effects of adding links and nodes or just duplicating links in the class 3/4 structure.

The purpose of these structures is to enable the further routing of a call from one toll family origin in one

primary domain to an adjacent primary domain. The multiplicity of links across the domains help to complete a call which may otherwise be blocked due to congestion, or trunk or node damage.

The methods available to increase the NETS MS in complete class 3/4 structures is either to duplicate existing links or to add links and nodes. Figure 7.12 delineates the advantages of duplicating links.

X-Y Design	Q	Q Increase per dup PP	Q Increase per dup PT	Q Increase per dup TP	Q Increase per dup TT
2-2	4	1	1	1	1
2-3	6	2	1	2	1
2-4	18	5	2	5	2
3-2	6	2	2	1	1
3-3	9	4	2	2	1
3-4	27	10	4	5	2
4-2	18	5	5	2	2
4-3	27	10	5	4	2
4-4	81	25	10	10	4

Figure 7.12 Effects of Duplicating Existing Links In Complete Class 3/4 Structures

From the table, the obvious link to duplicate in a complete class 3/4 structure is the one which provides the greatest increase in Q (redundant paths) per link. In an emergency situation it may be impractical to duplicate the optimal link, therefore the values in the table will prove useful when looking for the second best way to increase survivability.

The second way to increase MS in a completed X-Y design is to add links and nodes to upgrade the X-Y design one complete step (e.g., from a 2-2 to 2-3 design). This requires:

(1) adding one class 4 (toll office).

(2) adding class 3/4 links.

(3) adding in-domain links (from primary to toll or toll to toll in the same domain).

(4) adding links between central offices and the new class 4 office (ST links).

Figure 7.12 shows the required changes for upgrading X-Y designs but does not include provisions for (4) above because of the many design possibilities for toll family structures.

Original design	New X-Y design	Added in-domain links	Added Class 3/4 links	Original Q	New Q
2-2	2-3	1(3-4) 1(4-4)	0	4	6
2-3	2-4	1(3-4) 2(4-4)	1(PT) 1(TT)	6	18
3-2	3-3	1(3-4) 1(4-4)	0	6	9
3-3	3-4	1(3-4) 2(4-4)	1(PT) 1(TT)	9	27
4-2	4-3	1(3-4) 1(4-4)	0	18	27
4-3	4-4	1(3-4) 2(4-4)	1(PT) 2(TT)	27	81
2-2	3-2	1(3-4) 1(4-4)	0	4	6
3-2	4-2	1(3-4) 2(4-4)	1(TP) 1(TT)	6	18
2-3	3-3	1(3-4) 1(4-4)	0	6	9
3-3	4-3	1(3-4) 2(4-4)	1(TP) 1(TT)	9	27
2-4	3-4	1(3-4) 1(4-4)	0	18	27
3-4	4-4	1(3-4) 2(4-4)	1(TP) 2(TT)	27	81

(3-4) = in-domain Class 3 to Class 4
(4-4) = in-domain Class 4 to Class 4

Figure 7.12 X-Y Design Upgrade Requirements

By comparing the previous two figures it is possible to determine the optimal method for improving MS for a given X-Y design. In every case with design upgrade the increase in Q requires at least two trunks and one office addition. The duplication of existing links method of Figure 7.11 proves to be the most efficient method of increasing surviv-ability. The tradeoffs for the two methods are exemplified in the following scenario. How many, and which type of class 3/4 links, in a 3-4 design, must be duplicated to

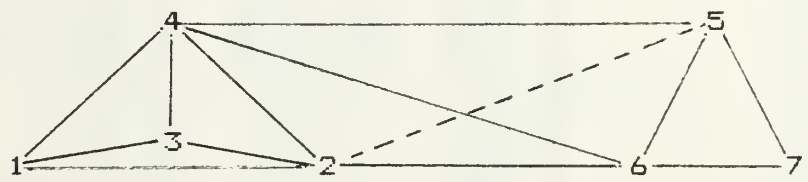
achieve the increase in Q which results from an upgrade of a 3-4 to 4-4 design ?

The upgrade increases Q from 27 to 81 and requires 3 in-domain trunks (1 primary-toll trunk and 2 toll-toll trunks), 1 TP trunk, 2 TT trunks, and one class 4 office.

The trunk duplication method requires 54 new paths or 5 more duplicated PP trunks (6 total) plus 1 more duplicated TP trunk (2 total).

2. Incomplete Class 3/4 Structure Tradeoffs

Figure 7.13 shows a 4-3 design class 3/4 structure that is incomplete. The incompleteness is caused by the missing TP link (25). What is the best way to increase Q ? Is it best to replace the missing link ?



1 PP (45) with TPW = 10
1 PT (46) with TPW = 5
1 TP (35) with TPW = 4
2 TT (26/36) with TPW = 2 each

Total (Q) = 23

Figure 7.13 Incomplete 4-3 Class 3/4 Design

The missing link (TP) causes a loss of 4 TPW. The priorities for duplicating or replacing links follows:

(1) Duplicate PP link, gain 10 TPW.

(2) Duplicate PT link, gain 5 TPW.

(3) Duplicate TP link (35), gain 4 TPW or add missing TP link, gain 4 TPW.

The table in Figure 7.14 provides all of the possible ways to have incomplete class 3/4 structures which are missing just one link. The table prioritizes the methods for increasing Q with the given design.

X-Y design	Missing link/ loss in Q	Pri 1/ Q gain	Pri 2/ Q gain	Pri 3/ Q gain	Pri 4/ Q gain
2-2	PP/1	R PP/1	D PT/1*	D TP/1*	D TT/1*
	PT/1	R PT/1	D PP/1*	D TP/1*	D TT/1*
	TP/1	R TP/1	D PP/1*	D PT/1*	D TT/1*
	TT/1	R TT/1	D PP/1*	D PT/1*	D TP/1*
2-3	PP/2	R PP/2	D TP/2*	D PT/1	D TT/1*
	PT/1	D PP/2	D TP/2*	D TT/1	R PT/1*
	TP/2	R TP/2	D PP/2*	D PT/1	D TT/1*
	TT/1	D PP/2	D TP/2*	D PT/1	R TT/1*
2-4	PP/5	R PP/5	D TP/5*	D PT/2	D TT/2*
	PT/2	D PP/5	D TP/5*	D TT/2	R PT/2*
	TP/5	R TP/5	D PP/5*	D PT/2	D TT/2*
	TT/2	D PP/5	D TP/5*	D PT/2	R TT/2*
3-2	PP/2	R PP/2	D PT/2*	D TP/1	D TT/1*
	PT/2	R PT/2	D PP/2*	D TP/1	D TT/1*
	TP/1	D PP/2	D PT/2*	D TT/1	R TP/1*
	TT/1	D PP/2	D PT/2*	D TP/1	R TT/1*
3-3	PP/4	R PP/4	D PT/2	D TP/2*	D TT/1
	PT/2	D PP/4	D TP/2	R PT/2*	D TT/1
	TP/2	D PP/4	D PT/2	R TP/2*	D TT/1
	TT/1	D PP/4	D PT/2	D TP/2*	R TT/1
3-4	PP/10	R PP/10	D TP/5	D PT/4	D TT/2
	PT/4	D PP/10	D TP/5	R PT/4	D TT/2
	TP/5	D PP/10	R TP/5	D PT/4	D TT/2
	TT/2	D PP/10	D TP/5	D PT/4	R TT/2
4-2	PP/5	R PP/5	D PT/5*	D TP/2	D TT/2*
	PT/5	R PT/5	D PP/5*	D TP/2	D TT/2*
	TP/2	D PP/5	D PT/5*	R TP/2	D TT/2*
	TT/2	D PP/5	D PT/5*	D TP/2	R TT/2*
4-3	PP/10	R PP/10	D PT/5	D TP/4	D TT/2
	PT/5	D PP/10	R PT/5	D TP/4	D TT/2
	TP/4	D PP/10	D PT/5	R TP/4	D TT/2
	TT/2	D PP/10	D PT/5	D TP/4	R TT/2
4-4	PP/25	R PP/25	D PT/10	D TP/10*	D TT/4
	PT/10	D PP/25	R PT/10	D TP/10*	D TT/4
	TP/10	D PP/25	D PT/10	R TP/10*	D TT/4
	TT/4	D PP/25	D PT/10	D TP/10*	R TT/4

* indicates no preference over priority in immediate left column

R = Replace D = Duplicate

Figure 7.14 Table for Class 3/4 Link Improvement (one link missing)

If missing more than one class 3/4 link in an X-Y design as in Figure 7.15 (missing 1 PP and 1 TP) it is necessary to use an algorithmic approach to determine the optimal method of increasing Q. The following algorithm for tradeoff analysis is provided.

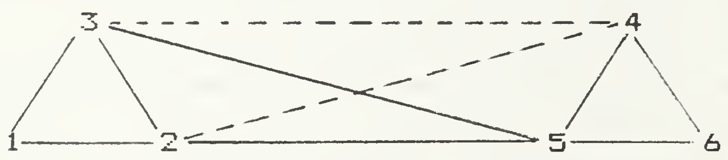


Figure 7.15 Class 3/4 Structure with Multiple Missing Links

a. Determine the TPW lost (TPWL) for each of the missing links (use Figure 7.14). Total the losses and call this "Qlost".

b. Determine the TPW for each of the remaining links (use Figure 7.14). Call this "TPWaa (where aa is either pp, pt, tp, or tt).

c. If Qlost < any 2(TPWaa) then duplicate aa and exit.

d. If Qlost > any 2(TPWaa) then replace missing links or duplicate multiple aa links until:

   Qlost <= 2(TPWaa) + 2(TPWbb) + ... + 2(TPWzz)
   or
   Qlost <= n(TPWaa) where n > 2, then exit.

The use of the algorithm is demonstrated for the incomplete design in Figure 7.15

a. missing PP (34), lost Q = 4
   missing TP (24), lost Q = 2

   Qlost = 6

b. remaining TP (35), TPWtp = 2;
   remaining TT (25), TPWtt = 1

c. Qlost > 2(TPWtp) and Qlost > 2(TPWtt);
   6 > 2(2) and 6 > 2(1)

d. Qlost > any 2(TPWaa) so replace PP (34) and TP (24) or make 3 duplicates of TP (35).

3. Summary of Class 3/4 Tradeoff Analysis

This section discussed ways of increasing the NETS PSN MS in class 3/4 link structures. For complete X-Y designs it is possible to increase survivability either by duplicating links or by upgrading the X-Y design one step. In either case there are tradeoffs involved. The simplest way to increase MS for complete designs is by duplicating existing class 3/4 links.

For incomplete class 3/4 designs two cases were discussed, missing one link and missing more than one link. For the first case a complete prioritized table is offered to determine optimal ways to increase the survivability. For the incomplete X-Y structure with multiple missing paths, an algorithm was presented.

C. TANDEM OFFICE PLACEMENT TRADEOFFS

When a tandem office is critical at either the origin central office structure or the destination central office structure, the MS is adversely affected (reduced by 25 percent, RMSt = 0.25). If tandem critical at both origin and destination central office structures, the MS is reduced by 50 percent (RMSt = 0.50). To increase the NETS MS when tandem offices are critical it is necessary to route trunks around the tandem office (by-pass it). The table in Figure 7.16 shows the tradeoffs associated with increasing MS by adding additional ST links to tandem-central office designs.

Origin RMSt	Dest. RMSt	Combined RMSt	Add ST at at origin	Add ST at At dest.	New RMSt
0.5	1.0	0.5	yes	n/a	1.0
0.5	0.5	0.25	yes	no	0.5
0.5	0.5	0.25	no	yes	0.5
0.5	0.5	0.25	yes	yes	1.0
1.0	0.5	0.5	n/a	yes	1.0

Figure 7.16 Tandem Office Placement Tradeoffs

From the table, the number of added ST links required to increase combined RMSt can be determined. Given initial combined RMSt = 0.5, 1 ST link is required to yield a new RMSt = 1.0. If original combined RMSt = 0.25, 1 ST link addition increases RMSt to 0.5 and 1 ST link added to each of the central designs increases RMSt to 1.0.

D. COMBINED ANALYSIS TRADEOFFS

From the previous three sections (toll family, class 3/4 structures, and tandem office placement), there are 16 unique combinations of NETS PSN designs to consider when conducting overall analysis tradeoffs. Figure 7.17 shows the conditions of each of the subset structures in each of the 16 cases.

Case	Origin Toll Family Condition	Dest. Toll Family Condition	Class 3/4 Link Structure Condition	Tandem Office Config
1	CC	CC	C	RE
2	CC	CC	C	CR
3	CC	CC	I	RE
4	CC	CC	I	CR
5	CC	PC	C	RE
6	CC	PC	C	CR
7	CC	PC	I	RE
8	CC	PC	I	CR
9	PC	CC	C	RE
10	PC	CC	C	CR
11	PC	CC	I	RE
12	PC	CC	I	CR
13	PC	PC	C	RE
14	PC	PC	C	CR
15	PC	PC	I	RE
16	PC	PC	I	CR

CC = completely connected   PC = partially connected

C = complete   I = incomplete
RE = tandem redundant   CR = tandem critical

Figure 7.17 Combined Analysis Conditions

1. Methods of Increasing MS for the Combined Cases

For each of the cases in Figure 7.17 (1-16) there are numerous approaches to take to increase the MS. The author suggests that for any given case a prudent approach would be to analyze the case tradeoffs using the following prioritized examinations. For some cases the examination schemes may not be practical or required, however, the sequence of examinations (Figure 7.18) is suitable for the general case.

2. Applications of Examination Methods to Cases

For any given case (1-16), the recommended sequence of subset examination is presented in Figure 7.19. Again, these are recommended sequences and apply only to general situations. If doubt exists, all examinations should be performed and all tradeoff requirements should be compared.

Examination	Subset Examined	Discussion
a.	Tandem office criticality	If one or both of the toll families is constrained by a critical tandem office, bypass the office(s). The requirement is 1 or 2 link additions. (Figure 7.16)
b.	Duplicate class 3/4 links or upgrade design	Duplication of one or more links in completed class 3/4 designs is preferred over other schemes because the added TPW will usually outweigh increases from a link duplication at a toll family. The requirements for upgrading a design are limited to adding 0, 1, or 2 class 3/4 links plus 2 or 3 in-domain links plus 1 node. Again, the added gain in TPW may outweigh toll family link doubling. (Figure 7.12)
c.	Duplicate or add class 3/4 links to incomplete X-Y designs	Same as above discussion. Refer to the algorithm sample for Figure 7.15.
d.	Duplicate or add toll family links to increase MS	Lowest potential per/link gain in most cases due to probablistic nature of toll family structures. Refer to algorithm examples given in Figures 7.5 and 7.7.

Figure 7.18 Sequence of Examinations

Case	Recommended examination sequence
1	b
2	a
3	c
4	a, c
5	d
6	a, d
7	c, d
8	a, c, d
9	d
10	a, d
11	c, d
12	a, c, d
13	d
14	a, d
15	c, d
16	a, c, d

Figure 7.19 Recommended Solutions for NETS Cases 1-16

3. An Example Use of the Prioritized Solution Guide

Figure 7.20 presents a NETS PSN structure with some of the sub-optimal designs. There is partial connectivity

in the origin toll family. The class 3/4 links are incomplete. The destination toll family is constrained with a critical tandem office. Using Figure 7.17 it can be associated with a "case 12" combined condition analysis problem.

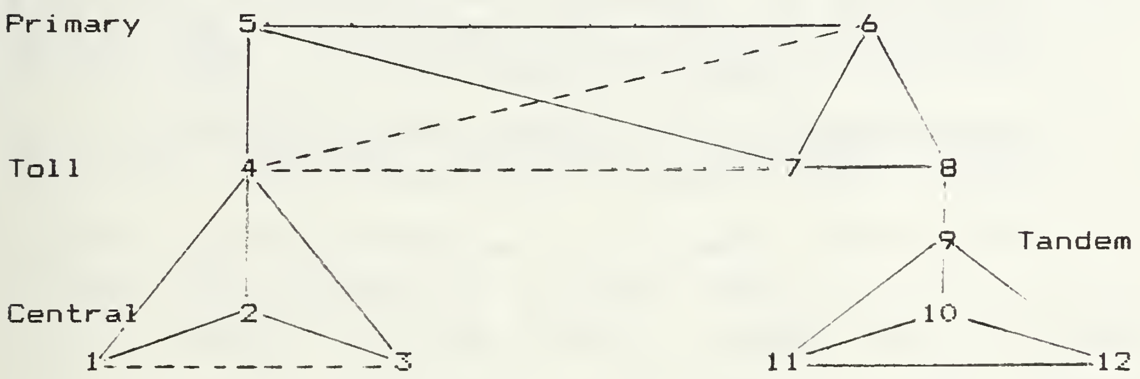


Figure 7.20 Prioritized Solution Example

Given the limiting capacity in the class 3/4 links as microwave, a MS (Measure of Survivability) for this scenario can be calculated. See the following steps.

a. RMSt (tandem criticality) = 0.5 (determined from Figure 6.28).

b. RMSc (limiting capacity) = 144 (Figure 6.29)

c. RMSf (toll family origin) = 2 (Epaths = 9/3 or 3 redundant paths from any origin (1,2,or 3)) from Figure 6.25

d. RMSf (toll family destination) = 3 (5 redundant paths from destination (12) to toll parent (9)) from Figure 6.25

e. RMSp (class 3/4 links) = 1 (2-3 design missing 1 TP with TPWL = 2 and 1 TT with TPWL = 1 (Figure 6.14) from Figure 6.26

f. $$MS = \frac{[RMSf(O)][RMSf(D)][RMSp][RMSc][RMSt]}{1050} \quad \text{(EQUATION 12)}$$

$$= \frac{[2][3][1][144][0.5]}{1050} = 0.411$$

The next step in the process is to use the recommended solution sequence from Figure 7.19 for a case "12". The chart calls for sequence a, c, d. The results in

increase of the sequence are presented in the following steps:

(1) Starting MS = 0.411

(2) Examination a: Bypass the critical tandem office at the destination by adding 1 link between 12 and 8. RMSt (new) = 1.0; MS = 0.823

(3) Examination c: Duplicate or add in the class 3/4 structure. Qlost= 3. Duplicate PP link (56) (or add TP link 46, if practical). Q(new)= 6. RMSp (new)=1. No change in RMSp; MS = 0.823

(4) Examination d: Duplicate or add in the origin toll family structure. Epaths for replacing link 1-3 is 4.667. RMSf is still 2. No change in MS.

From this example it is evident that the changes required for an increase in MS for a given structure may be discovered only through careful analysis of each of the subsets.

E. SUMMARY

Given a particular PSN NETS structure there are two ways to increase redundancy thereby increasing MS. One way is by adding links (or duplicating them). The second way is by adding both links and nodes.

The subset analysis method enables the user to examine each area (toll family, class 3/4 structures, and tandem office placement) for ways to increase the survivability.

For toll family tradeoff analysis, the concept of equal probability for any central office being the destination office (or origin office) was introduced. This probability was represented by the equation 1/(N-1) for an N node toll family. In completely connected families it was found that duplicating links provides a measure of Expected Redundancy Addition or ERA. The ERA for a given duplicated type of link (ST or SS) was found to vary from structure to structure. In partially connected families an algorithmic approach is taken to determine the effects of adding links. In some cases, the tradeoffs revealed that it is better to duplicate an existing link than to replace a missing link.

This methodology introduced the concept of Expected Number of Redundant Paths (Epaths).

In the class 3/4 structures a similar algorithmic approach to replacing or duplicating links was used. Again in some incomplete class 3/4 structures it was more effective to duplicate an existing link than to add the missing link. A prioritized list for increasing redundancy in the incomplete structure was provided.

For increasing survivability in the tandem placement the tradeoffs involved were adding one ST link to bypass the critical tandem office. The new ST link at this site increased MS by either 25 or 50 percent.

For determining the tradeoffs involved for an entire NETS structure a sequence of examinations in each of the subsets was recommended. Any given PSN design can be categorized into one of 16 "cases". Probably the one event which will increase MS the most is the bypassing of the critical tandem office. Other examination areas included investigating the tradeoffs of duplicating or adding links in the class 3/4 structure and in the toll family structure.

For calculating MS when the equally probable origin and destination condition exists, a new determinant for RMSf is used. This new estimate includes the probablistic nature of the origin and destination central office.

VIII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The survivability of the PSN is dependent upon the engineered design of the system and the ways that this design increases redundancy or lends itself to the potential increase in routing redundancy.

This research has shown the importance of examining the total network through subset analysis. This analytical method enables the researcher to view the details of each small component of an immense system and to pinpoint the ways to increase survivability. Once the subset analyses are completed, the results from each examination may be collated in a bottom-up fashion to produce the entire system analysis.

The PSN survivability is dependent upon the redundancies built into each of the subsets. The toll family subset redundant paths coupled with the class 3/4 design redundancies, trunk capacities, and tandem office placement considerations provide a multiplicity of redundancy.

The approach, in toll family analysis and class 3/4 structure analysis, of beginning with optimal connectivity and then removing links and nodes, lends itself to a comprehensible analysis of the real PSN, the partially connected network.

Specific network designs were deliberately not provided as the multitude of varieties was beyond the scope of this study. General network models for the NETS scenarios provided in the thesis provide a solid framework upon which to base future related research.

The development of a Measure of Survivability (MS), through the compilation of individual Relative Measures of Survivability (RMS) for the network subsets was in concert

with the general scheme of the study. This overall measurement provides a relative comparison between general network designs in the telephone network. The MS is not the only measure of survivability for the PSN as it is primarily based upon redundant routing. Other measures are certainly applicable and warrant future investigation.

B. RECOMMENDATIONS

1. Recommendations for Redundant Routing

The PSN is a vital element of National Security. It is the major carrier of voice and data transmissions for millions of Americans. In times of disasters the PSN must provide the capacity for hosting communications regardless of the scope of damage incurred by the network. Redundant routing, the multiple paths between the network users is crucial. With a multitude of severed links and destroyed nodes, the network must continue to provide a reliable means of two-way voice and data transmission through the surviving telecommunication trunks and switching centers.

The network subsets, (toll families and class 3/4 structures), if damaged beyond the point of providing the required capacities must be repaired. This research has shown that the repairs may be effected in ways other than total replacement. In some cases replacing a damaged link may not be as effective as duplicating an existing link. Replacing damaged offices may be infeasible or impractical. Improving or restoring communications may be accomplished with the bypassing of a damaged office (as in the case of a tandem critical office).

Existing architectural designs which best lend themselves to survivability are those with numerous nodes and duplicate links between the nodes. Designs which approach complete connectivity are the most durable and may survive specific disasters better than those which are less complete. Adjacent primary areas where there are numerous

class 3/4 links between domains are more survivable than those which have less links. Designs which have highly complex routing schemes appear to exhibit more survivability than those which use simple hierarchical routing.

This study has shown the importance of routing redundancy in the Public Switched Network in emergency situations. Prior to any NETS scenario, it is imperative that research be conducted to determine which portions of the PSN are the least survivable with regards to redundancy.

2. Research of Other Measures of Survivability

This thesis was based upon routing redundancy. Other approaches for measures of survivability need to be investigated. Areas of potential research include survivability of NETS based upon hierarchical office capabilities or new media technology. Questions to be answered include:

What amount of traffic can be handled at each class of the PSN switching offices ?

How are the newer technology media (satellite, optical fiber, waveguide) contributing to NETS/PSN survivability ?

What are the differences in NETS survivability when different types of disasters are encountered ? Is one type of PSN design more suitable to handle the effects of nuclear war than another ?

3. Feasibility Studies Concerning Redundant Routing

Some telephone network structures do not have built-in redundancy. It is necessary to conduct financial, technological, and operational feasibility studies to determine if improvements to the PSN through redundant routing can be effected.

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Thesis
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c.1 Increased survivability of the Nationwide Emergency Telecommunications System (NETS) through redundant routing.